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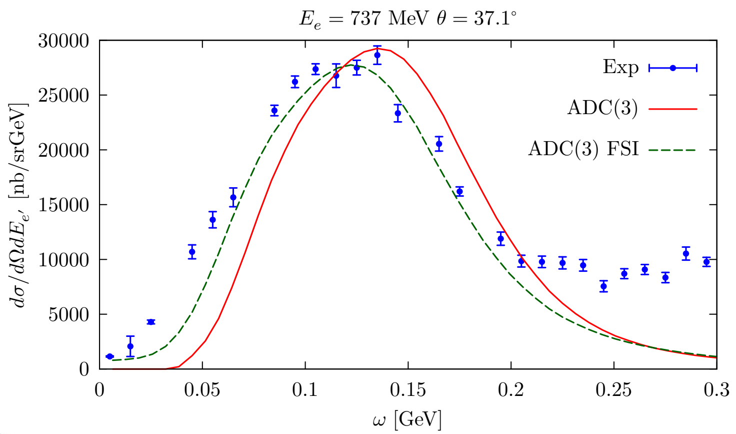
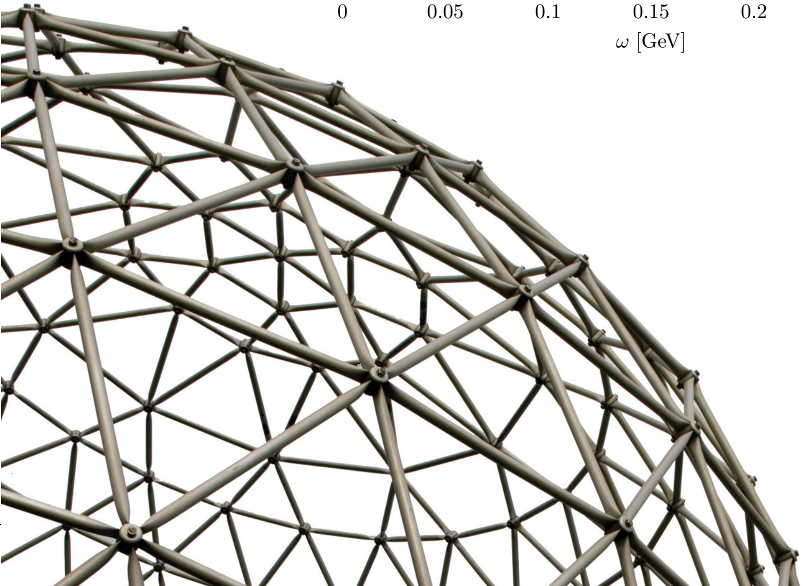
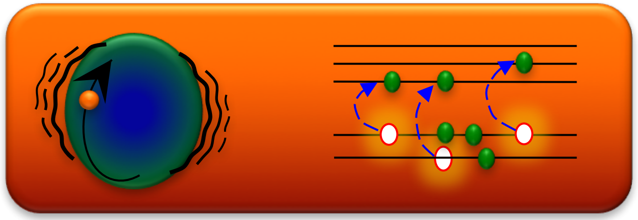
Use of ab initio approaches for accurate lepton-nucleus scattering

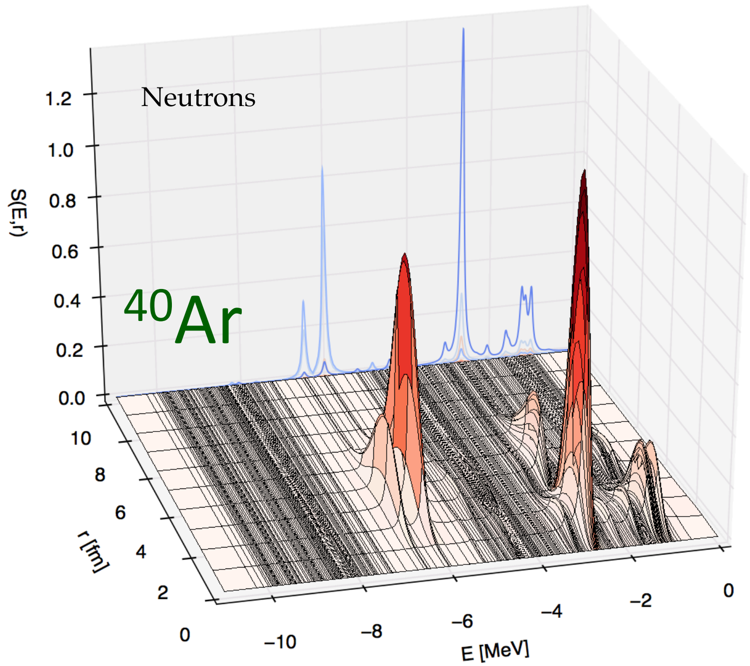
Carlo Barbieri — University of Surrey

10 July 2018







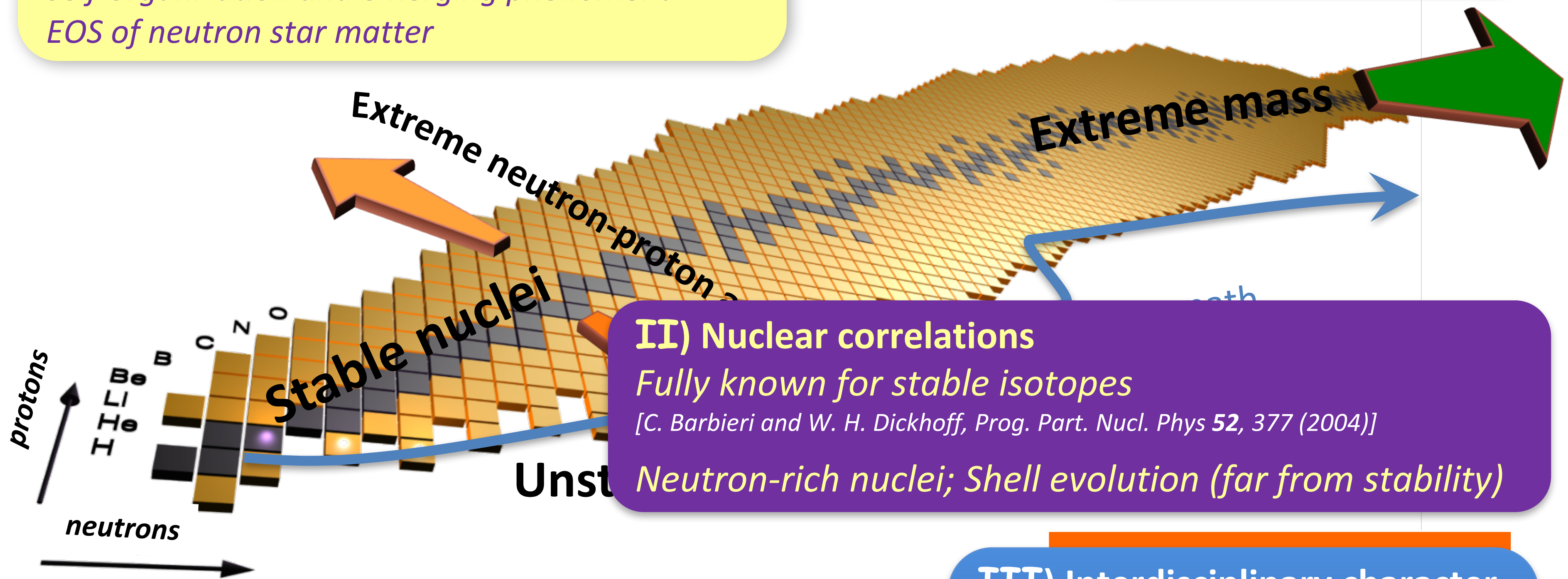


Current Status of low-energy nuclear physics

Composite system of interacting fermions

Binding and limits of stability
Coexistence of individual and collective behaviors
Self-organization and emerging phenomena
EOS of neutron star matter

Experimental programs
RIKEN, FAIR, FRIB…



II) Nuclear correlations

Fully known for stable isotopes

[C. Barbieri and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*

Neutron-rich nuclei; Shell evolution (far from stability)

I) Understanding the nuclear force

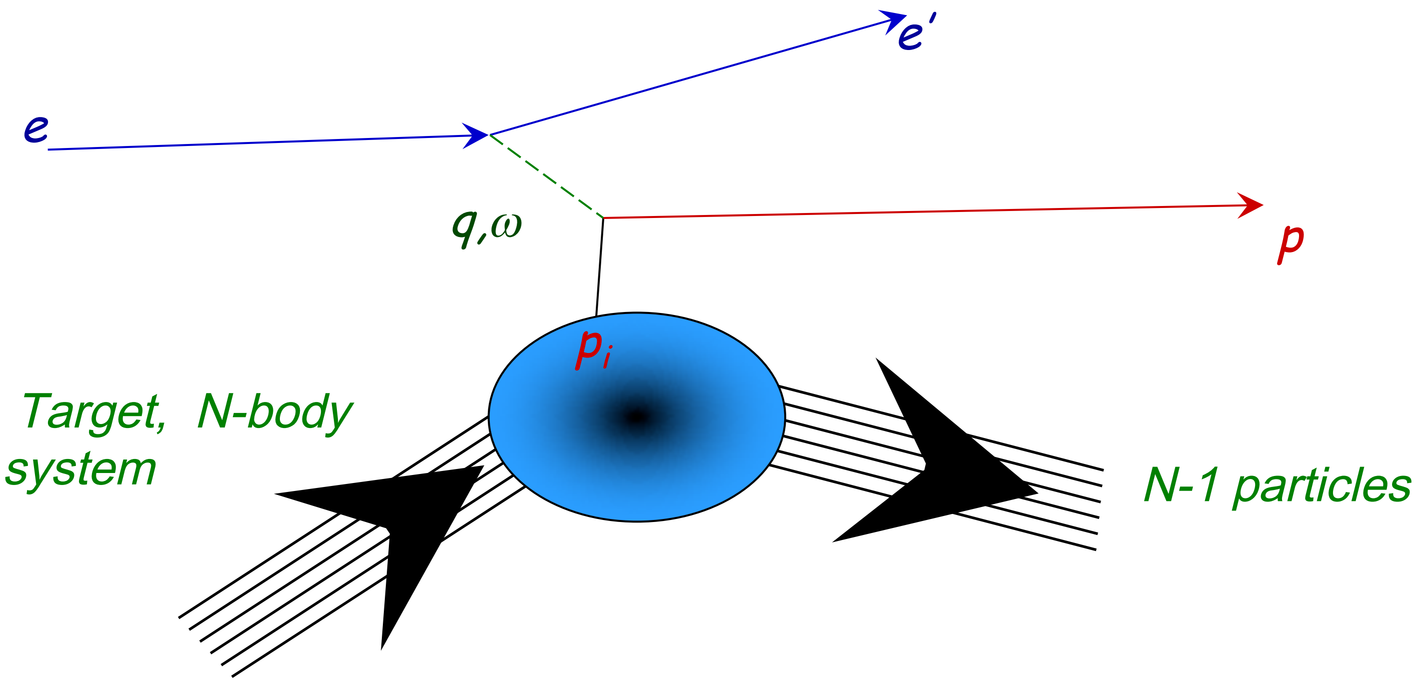
QCD-derived; 3-nucleon forces (3NFs)
First principle (ab-initio) predictions

III) Interdisciplinary character

Astrophysics
Tests of the standard model
Other fermionic systems:
ultracold gasses; molecules;

Spectroscopy via knock out reactions-basic idea

Use a probe (ANY probe) to eject the particle we are interested to:



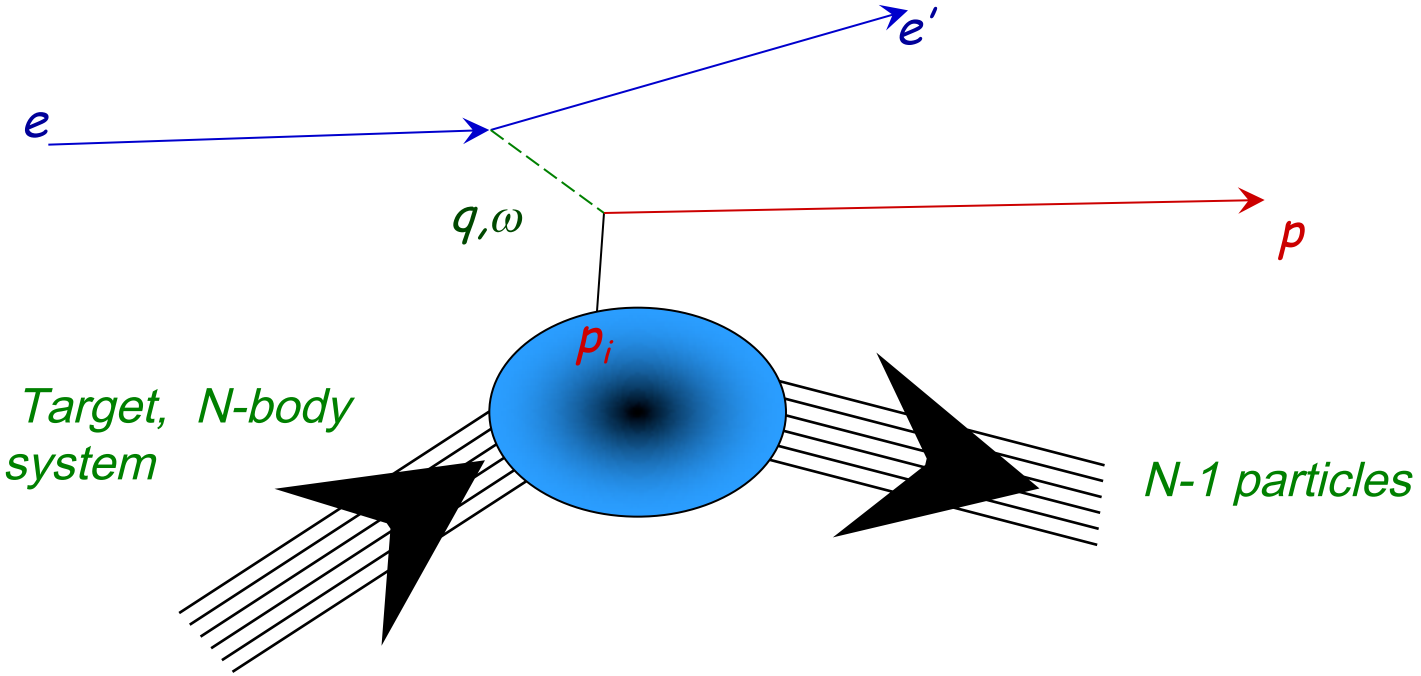
Basic idea:

- we know, e, e' and p
- "get" *energy and momentum* of p_i: $p_i = k_e' + k_p - k_e$
  $E_i = E_e' + E_p - E_e$

Better to choose large transferred momentum and weak probes!!!

Spectroscopy via knock out reactions-basic idea

Use a probe (ANY probe) to eject the particle we are interested to:

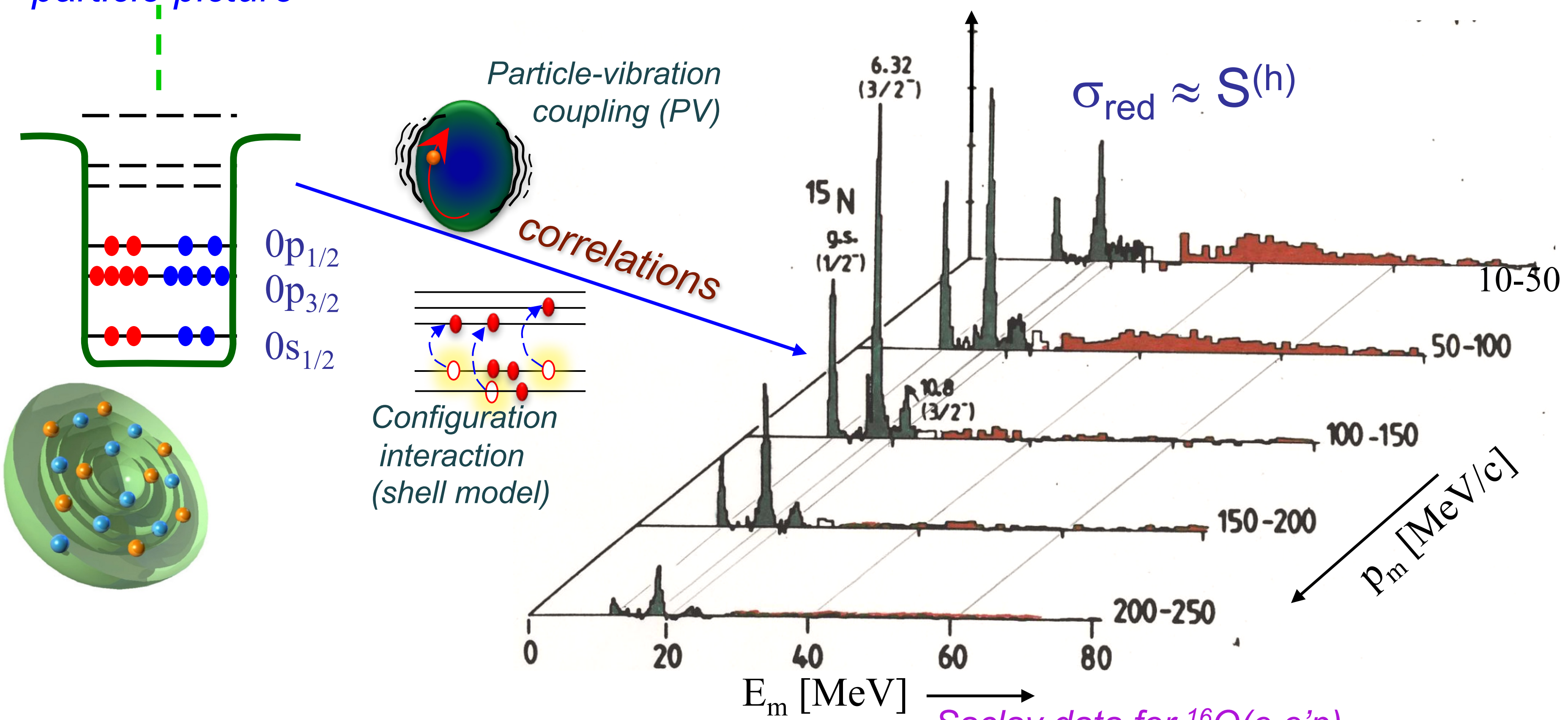


In plane wave impulse approximation (PWIA):

$$\frac{d\sigma_{(e,e'p)}}{dE_{e'}\, d\Omega_{e'}\, d\Omega_p} = \sigma_{ep} \times S^h(p_m, E_m)$$

Concept of correlations

Spectral function: distribution of momentum (p_m) and energies (E_m)



Saclay data for $^{16}O(e,e'p)$
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

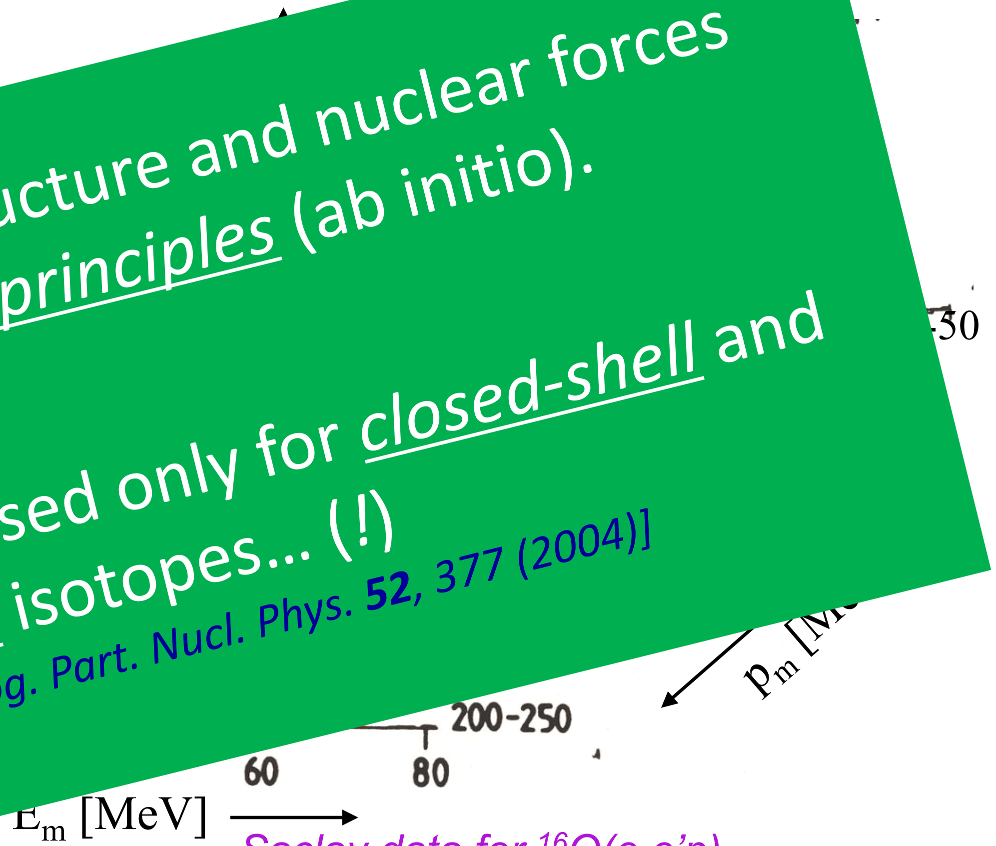
Understood for a few stable closed shells:
*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

Concept of correlations

independent particle picture

Particle-vibration

Spectral function: distribution of momentum (p_m) and ... E_m)



Saclay data for $^{16}O(e,e'p)$

[Mougey et al., Nucl. Phys. A335, 35 (1980)]

Want to understand structure and nuclear forces directly from first principles (ab initio).

So far, fully characterised only for closed-shell and stable isotopes… (!)

[W. Dickhoff, CB, Prog. Part. Nucl. Phys. **52**, 377 (2004)]

Unders… for a few stable closed shells:

*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

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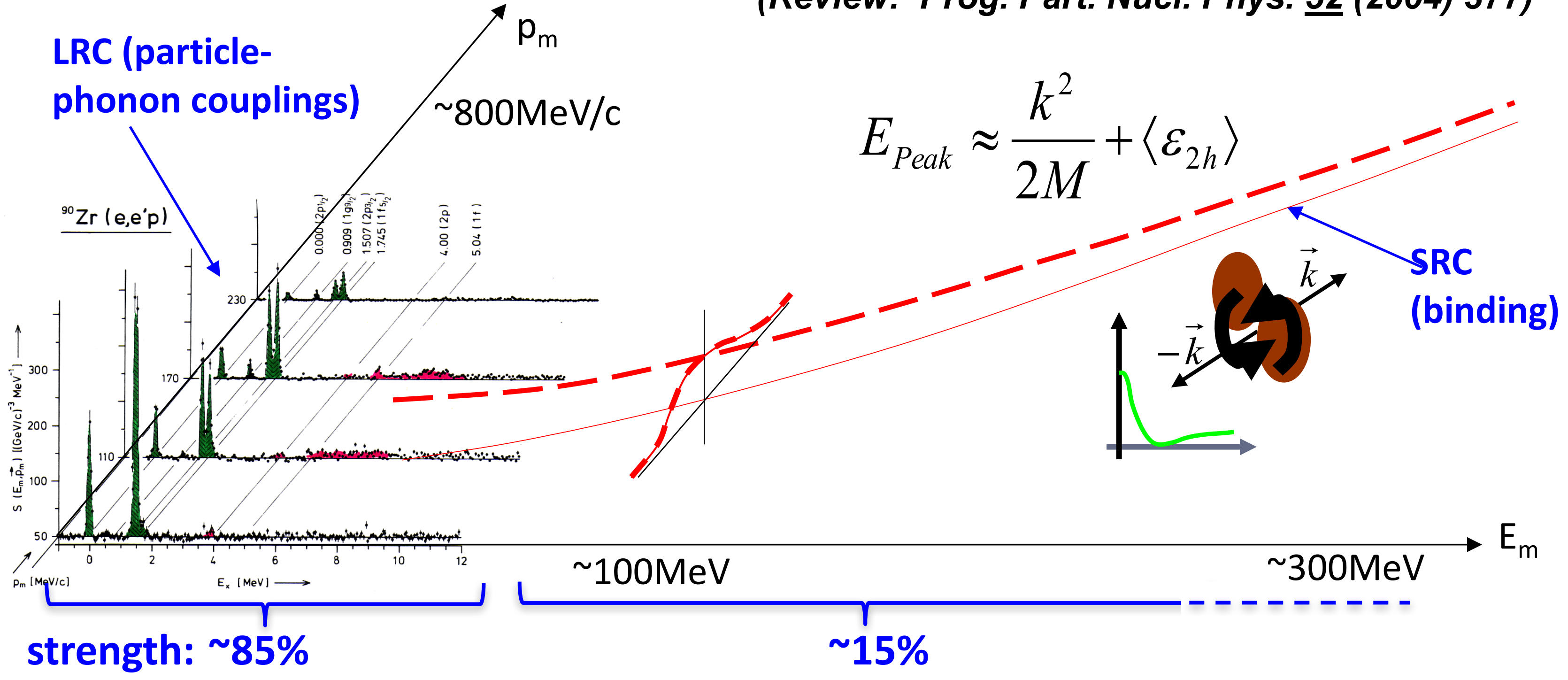
Distribution of (All) the Nuclear Strength

(Review: Prog. Part. Nucl. Phys. 52 (2004) 377)



Interest in short range correlations:

- a fraction of the total number of nucleons:
  - ~10% in light nuclei (VMC, FHNC, Green's function)
  - 15-20% in heavy systems (CBF, Green's function)
- can explain up to 2/3 of the binding energy [see ex. PRC51, 3040 ('95) for ^{16}O]
- influence NM saturation properties [see ex. PRL90, 152501 ('03)]

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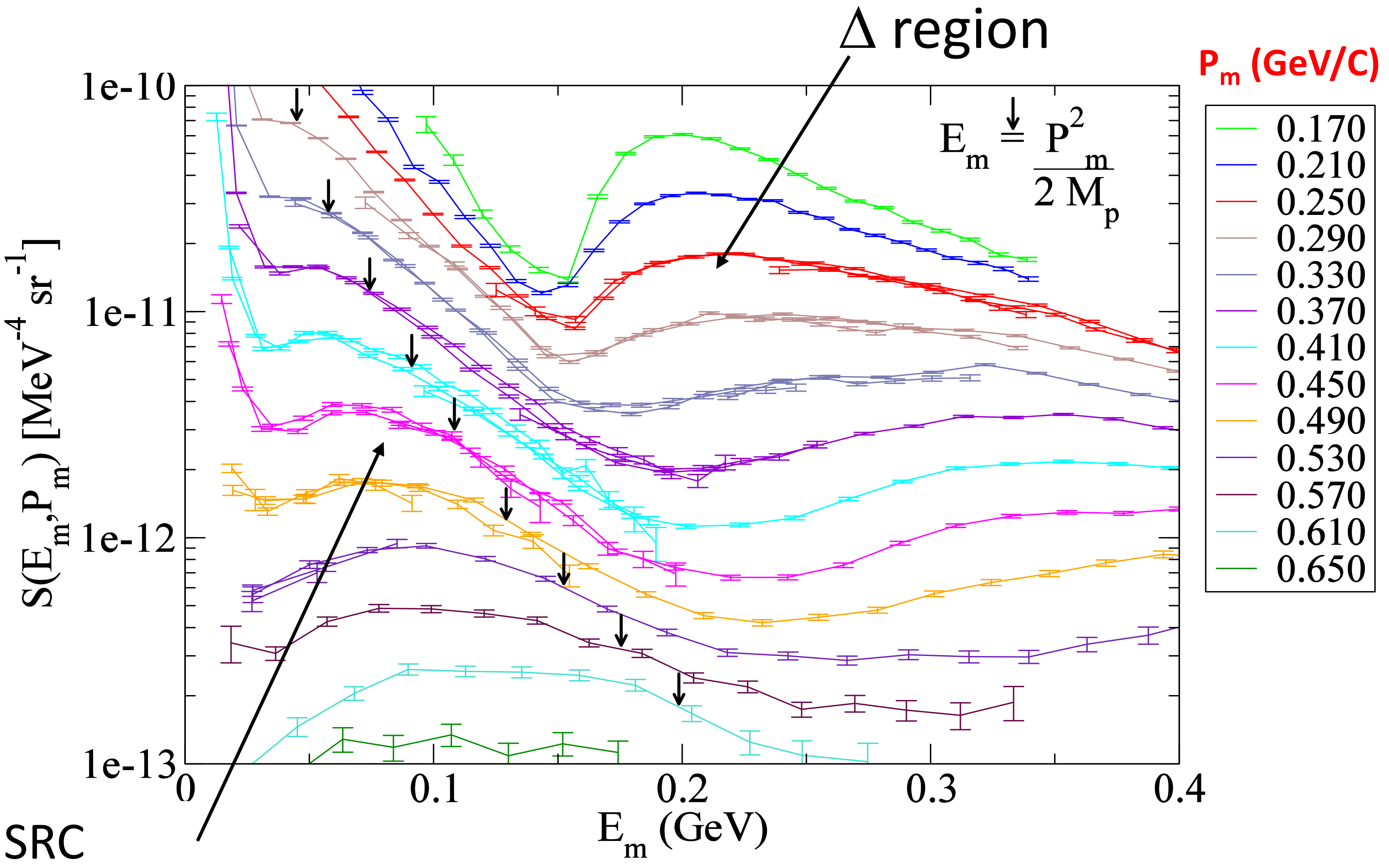
Spectral strength of ^{12}C from exp. E97-006



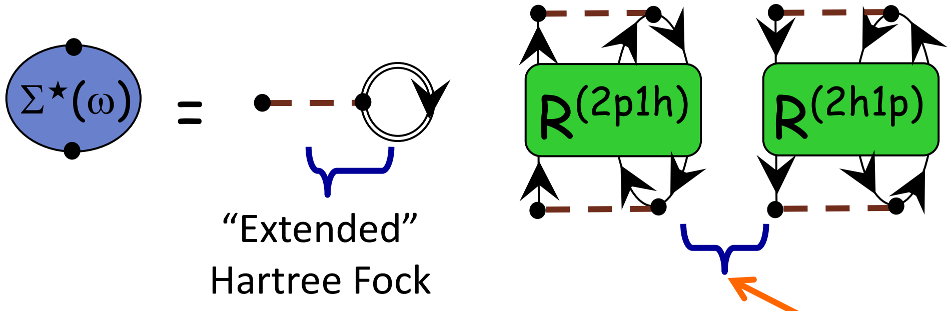
SRC correlations

D.Rohe, et. al, Eur. Phys. J. **A17**, 349 (2003),
Phys. Rev. Lett. **93** 182501 (2004).

The FRPA Method in Two Words

Particle vibration coupling is the main mechanism driving the redistribution and fragmentation of particle strength—expecially in the quasielastic regions around the Fermi surface…

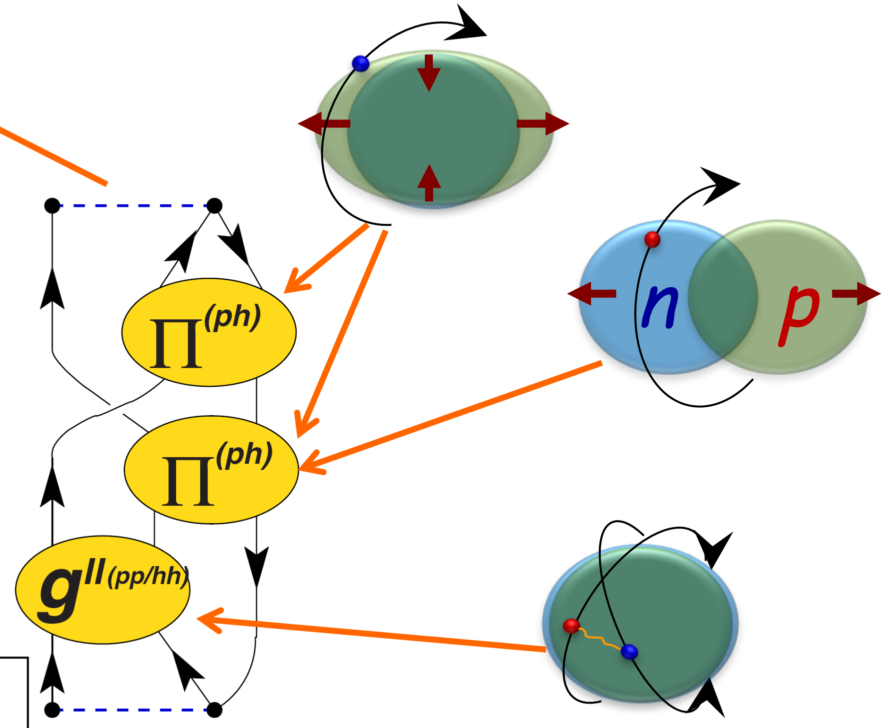
CB et al.,
Phys. Rev. C**63**, 034313 (2001)
Phys. Rev. A**76**, 052503 (2007)
Phys. Rev. C**79**, 064313 (2009)

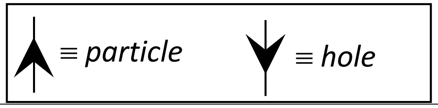


- A complete expansion requires *all types* of particle-vibration coupling

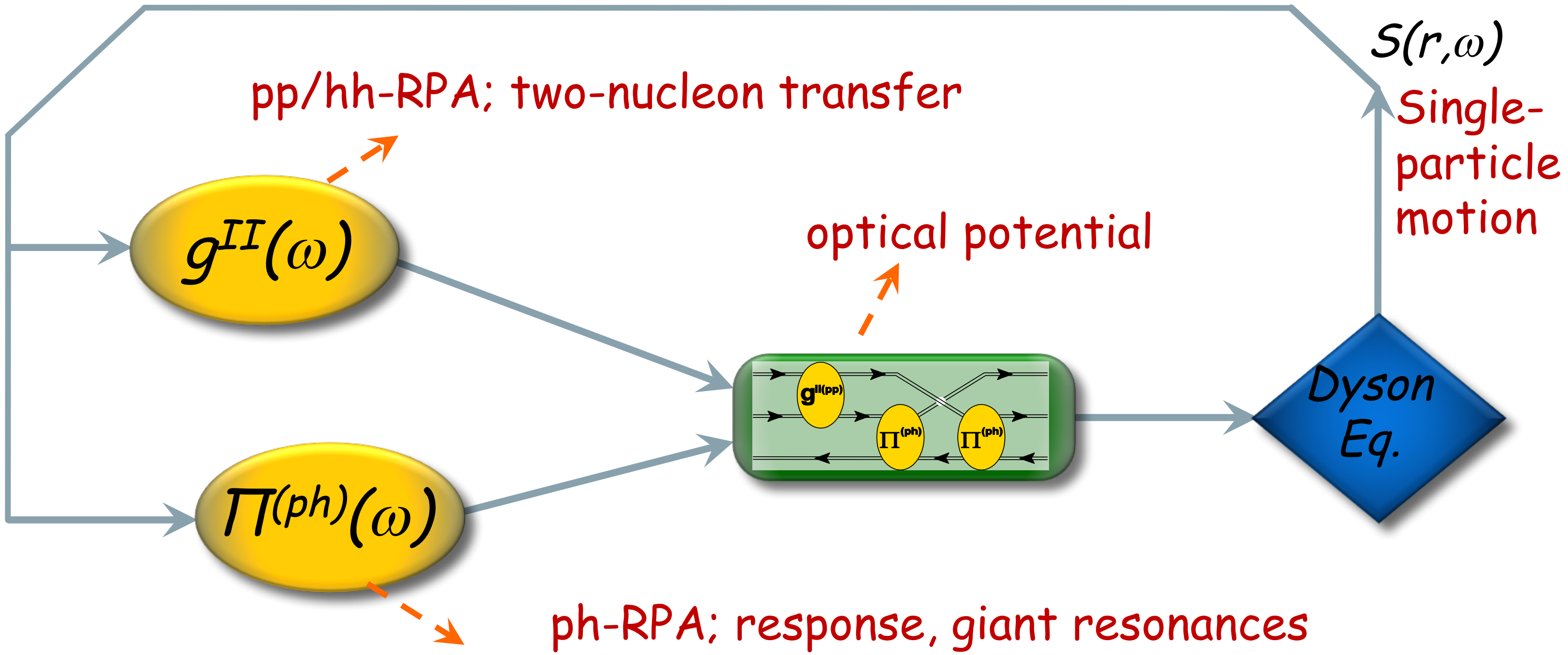
…these modes are all resummed exactly and to all orders in a *ab initio* many-body expansion.

- The Self-energy $\Sigma^{\star}(\omega)$ yields *both* single-particle states and scattering





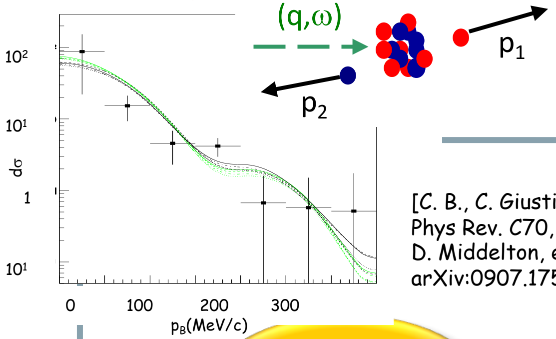
Self-Consistent Green's Function Approach



- Global picture of nuclear dynamics
- Reciprocal correlations among effective modes
- Guaranties *macroscopic conservation laws*

Self-Consistent Green's Function Approach

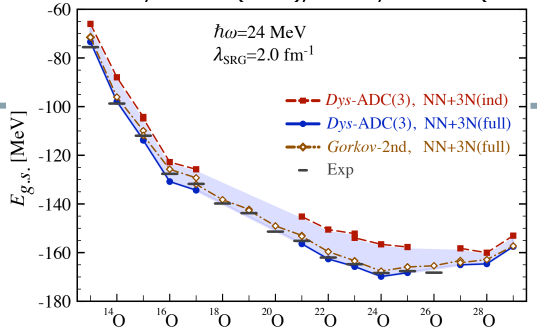
$^{16}O(e,e'pn)^{14}N$ @ MAINZ



[C. B., C. Giusti, et al.
Phys Rev. C70, 014606 (2004)
D. Middelton, et al.
arXiv:0907.1758; EPJA in print]

Binding energies

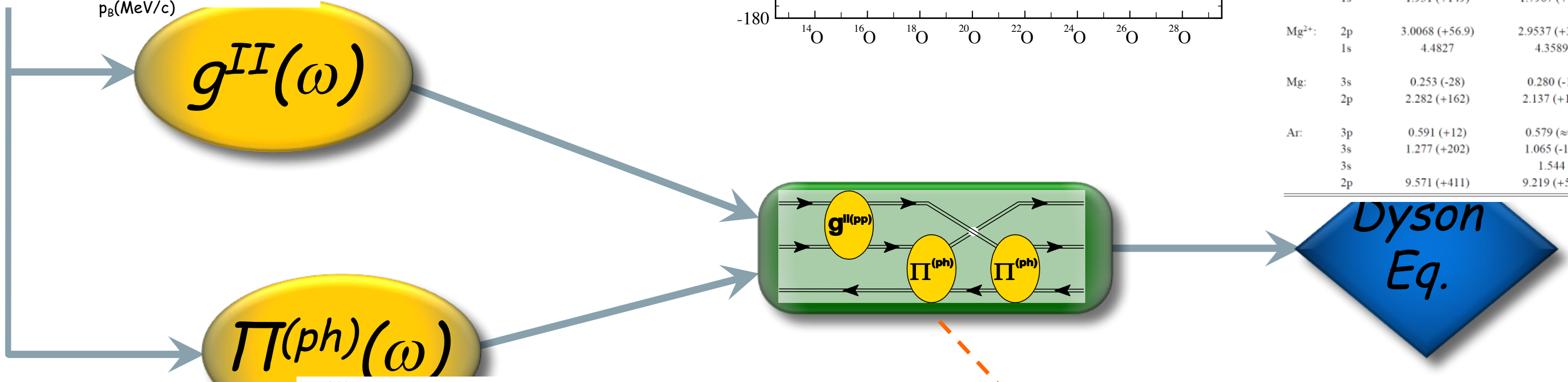
[PRL. 111, 062501 (2013),
PRC 92, 014306 (2015), PRC89, 061301R (2014)]



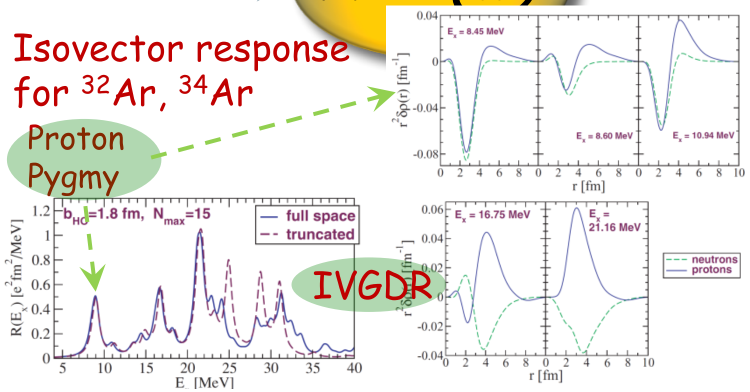
Ionization energies/ affinities, in atoms

[CB, D. Van Neck,
AIP Conf.Proc.1120,104 ('09) & in prep]

		Hartree-Fock	FRPAc	Experiment [16, 17]
He:	1s	0.918 (+14)	0.9008 (-2.9)	0.9037
Be^{2+}:	1s	5.6672 (+116)	5.6551 (-0.5)	5.6556
Be:	2s	0.3093 (-34)	0.3224 (-20.2)	0.3426
	1s	4.733 (+200)	4.5405 (+8)	4.533
Ne:	2p	0.852 (+57)	0.8037 (+11)	0.793
	1s	1.931 (+149)	1.7967 (+15)	1.782
Mg^{2+}:	2p	3.0068 (+56.9)	2.9537 (+3.8)	2.9499
	1s	4.4827	4.3589	
Mg:	3s	0.253 (-28)	0.280 (-1)	0.281
	2p	2.282 (+162)	2.137 (+17)	2.12
Ar:	3p	0.591 (+12)	0.579 (≈0)	0.579
	3s	1.277 (+202)	1.065 (-10)	1.075
	3s		1.544	
	2p	9.571 (+411)	9.219 (+59)	9.160

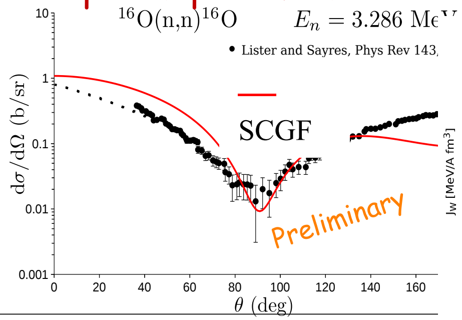


Isovector response for ^{32}Ar, ^{34}Ar

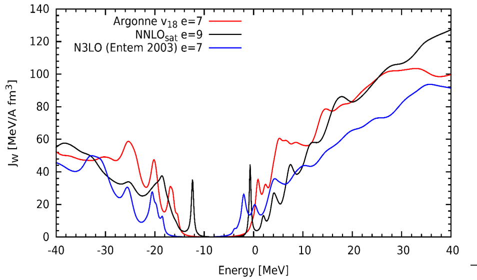


[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Optical potential



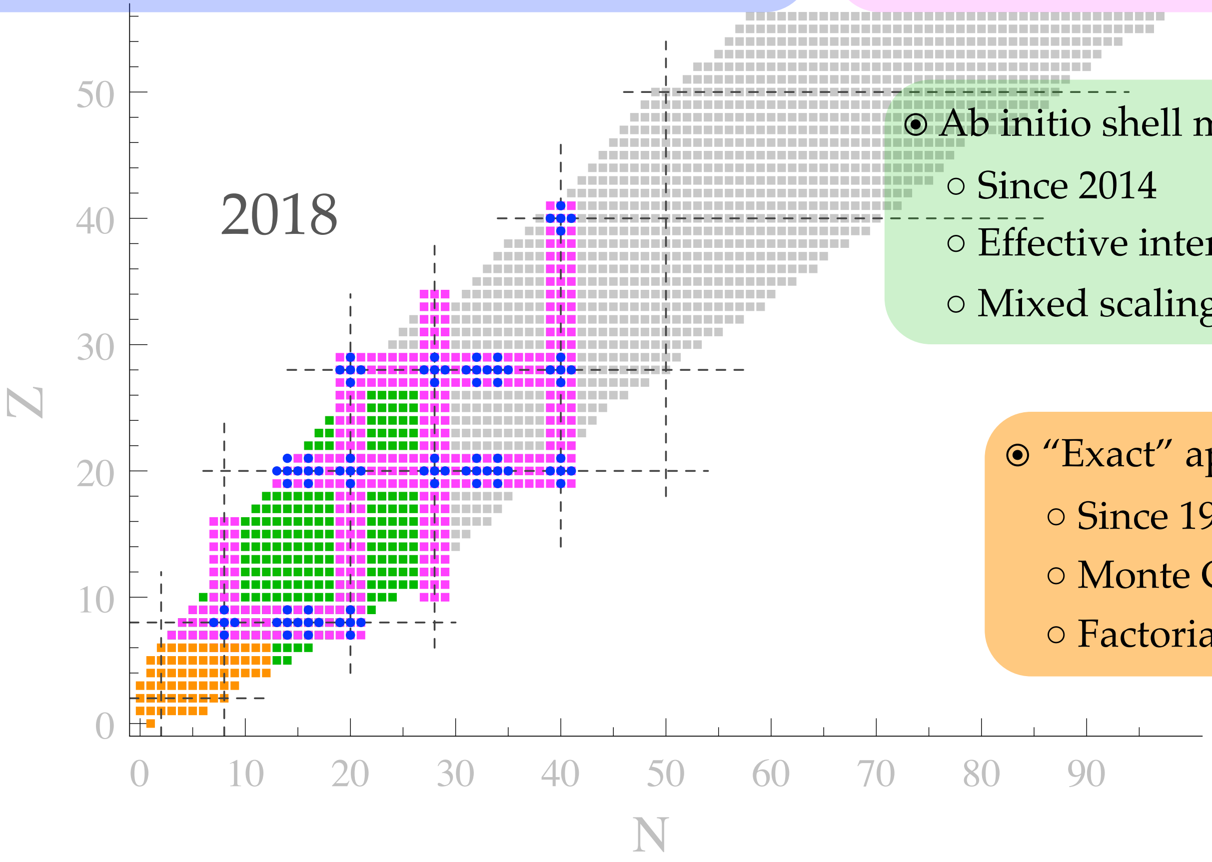
arXiv:1612.01478 [nucl-th]



Reach of ab initio methods across the nuclear chart

- Approximate approaches for closed-shell nuclei
  - Since 2000's
  - SCGF, CC, IMSRG
  - Polynomial scaling

- Approximate approaches for open-shells
  - Since 2010's
  - GGF, BCC, MR-IMSRG
  - Polynomial scaling



- Ab initio shell model
  - Since 2014
  - Effective interaction via CC/IMSRG
  - Mixed scaling

- "Exact" approaches
  - Since 1980's
  - Monte Carlo, CI, …
  - Factorial scaling

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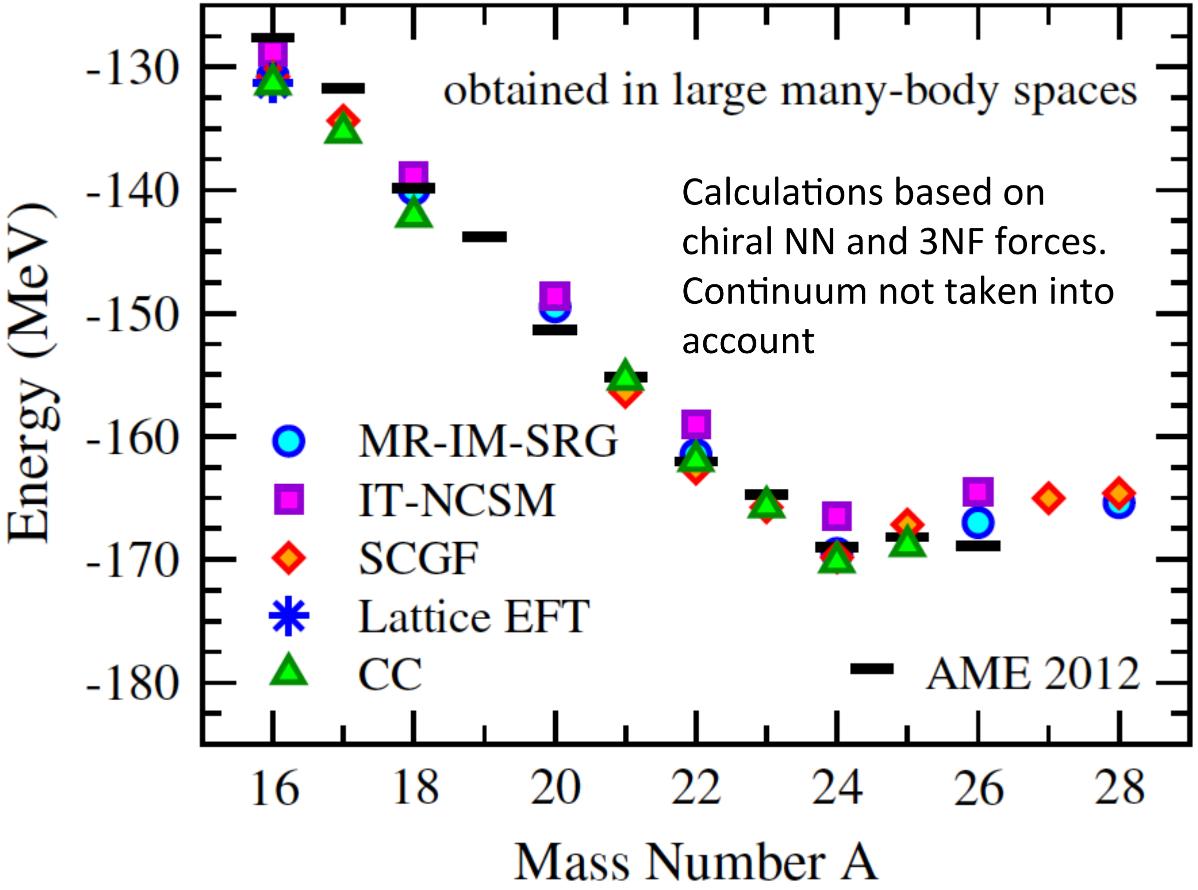
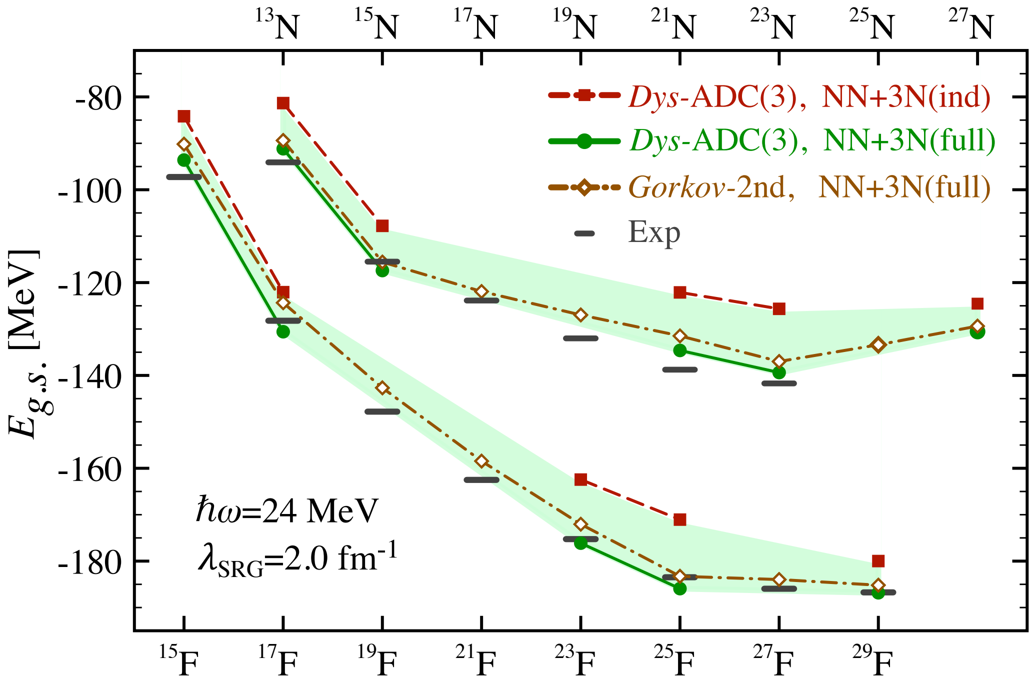
Slide, courtesy of V. Somà

Benchmark of ab-initio methods in the oxygen isotopic chain



Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)
and Phys. Rev. C **92**, 014306 (2015)



→ 3NF tensor and 3NF near flourine's dripline

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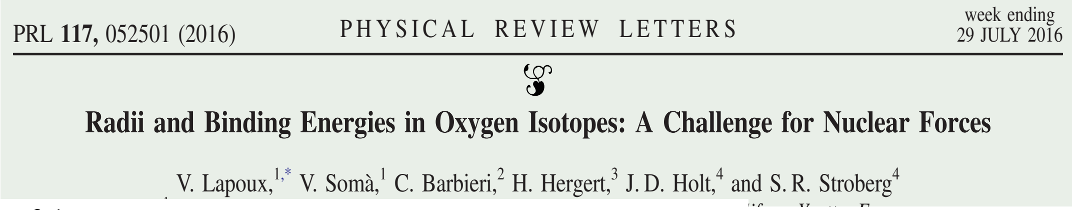
N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

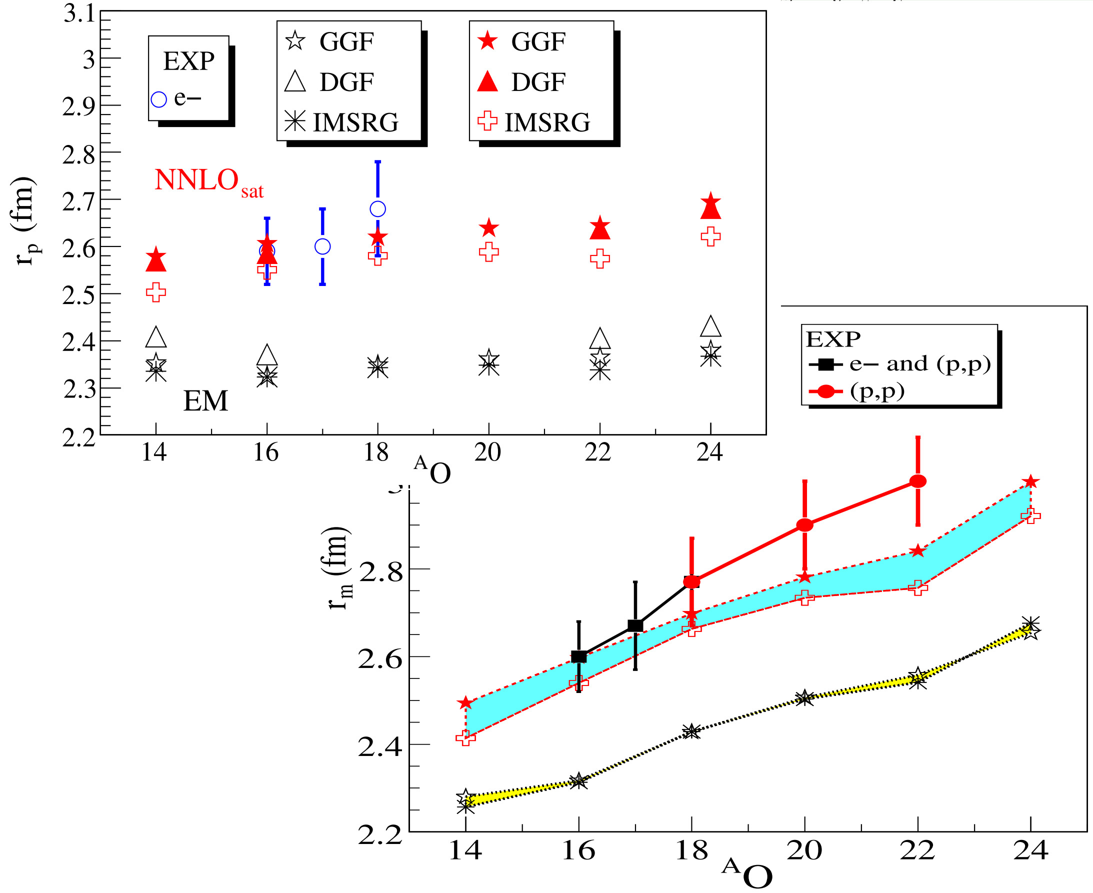
Comparison of nuclear forces – ^{A}O and $^{A}Si/^{A}S$



PRL **117**, 052501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

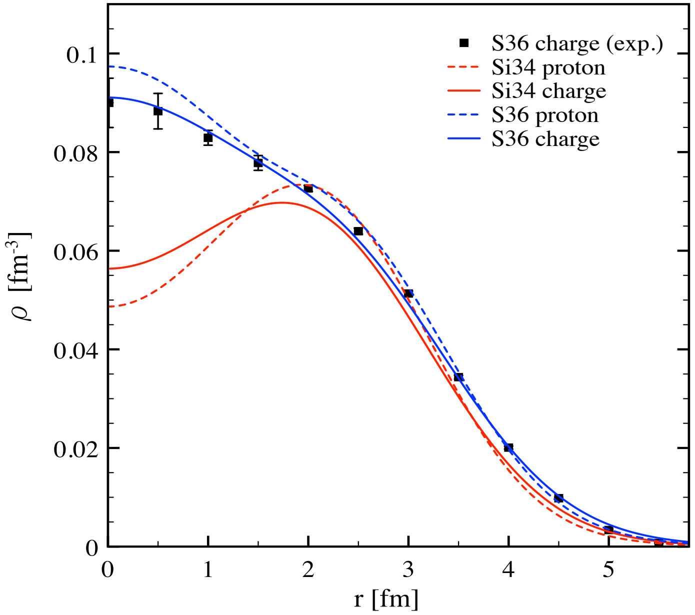
V. Lapoux,[1,*] V. Somà,[1] C. Barbieri,[2] H. Hergert,[3] J. D. Holt,[4] and S. R. Stroberg[4]



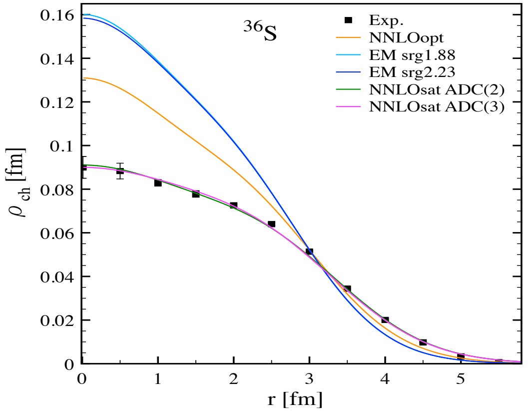
Saturation and radii now predicted <u>*accurately*</u>!

Duguet, Somà, Lecuse, CB, Navrátil, Phys.Rev. C**95**, 034319 (2017)

- ^{34}Si is unstable, charge distribution is still unknown
- Suggested central depletion from mean-field simulations
- *Ab-initio* theory confirms predictions
- Other theoretical and experimental evidence: *Phys. Rev. **C 79**, 034318 (2009), Nature Physics **13**, 152–156 (2017).*

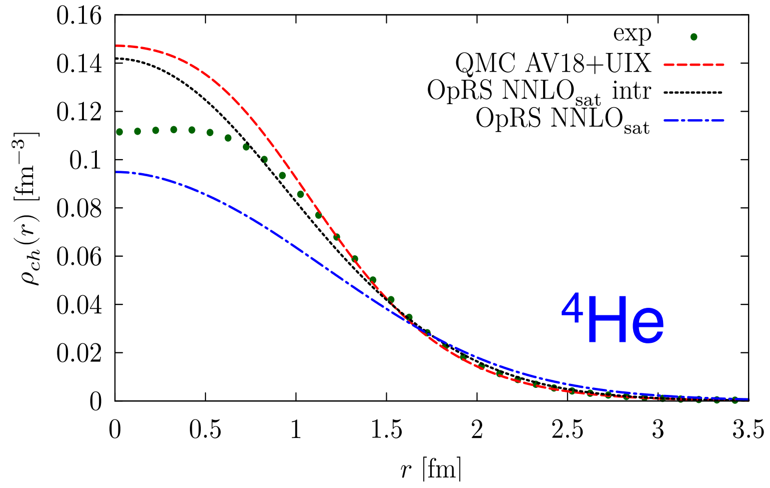


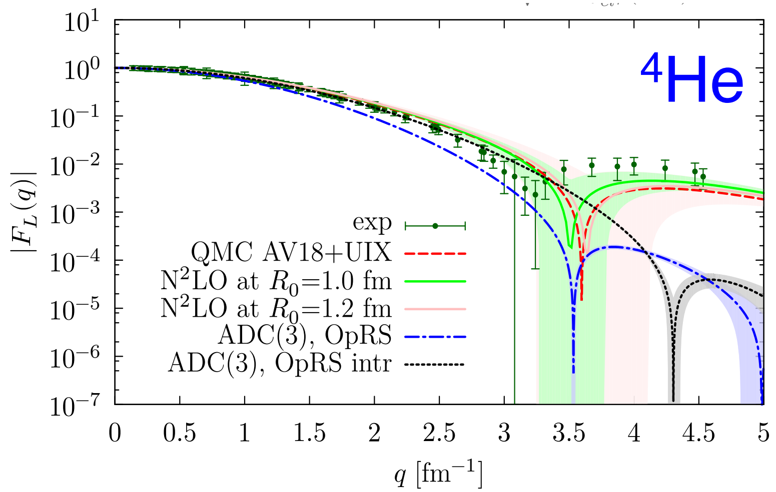
<u>Validated</u> by charge distributions and neutron quasiparticle spectra:

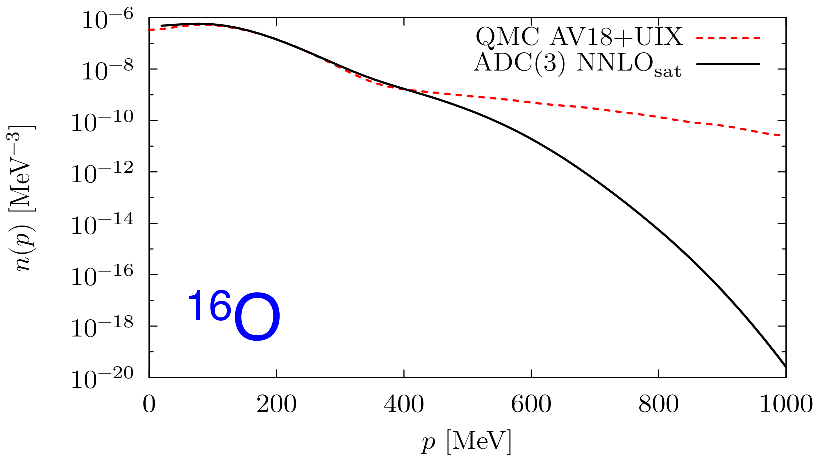


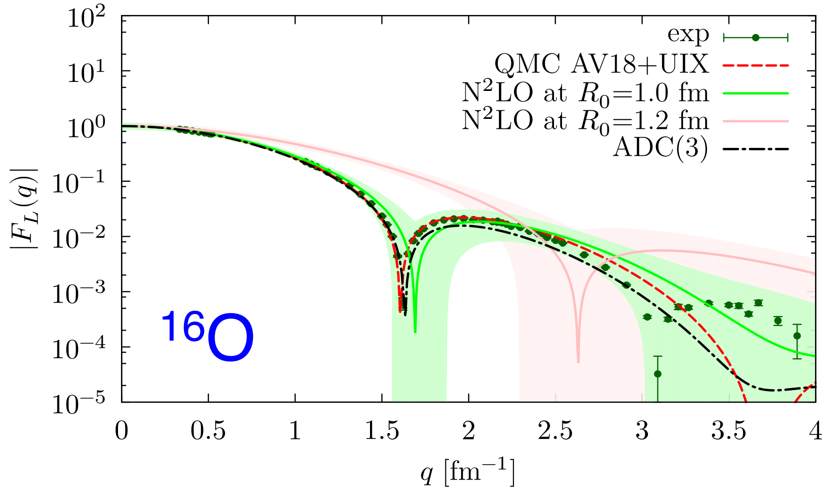
Prediction for chrg./mom. distributions and form factors

$$F_L(\mathbf{q}) = \frac{1}{Z} \frac{G_E^p(Q_{el}^2)\tilde{\rho}_p(q) + G_E^n(Q_{el}^2)\tilde{\rho}_n(q)}{\sqrt{1+Q_{el}^2/(4m^2)}}$$







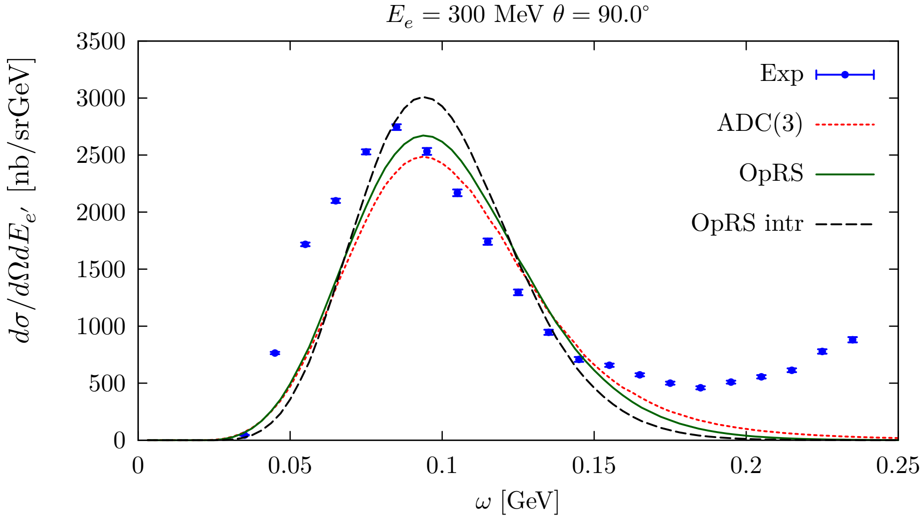


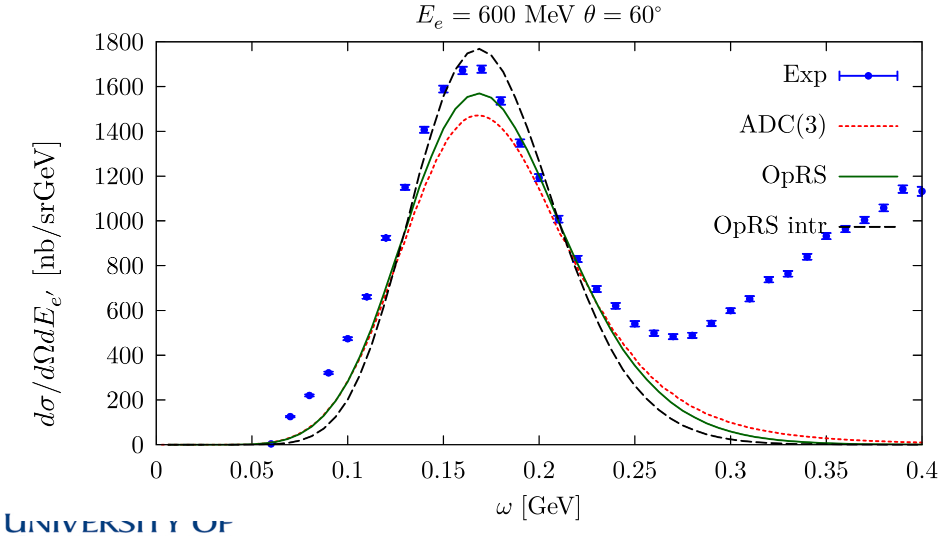
- Calculations from the spectral functions obtained using SCGF
- Based on the saturating chiral N2LO-sat nuclear force
- Comparison to QMC calculations based on local chiral forces and/or AV18+UIX
[PRC96, 024326 ('17)
PRC96, 054007 ('17)
PRC97, 044318 ('18)]

N. Rocco, CB, arXiv:1803.00825 (Phys. Rev. C in print)

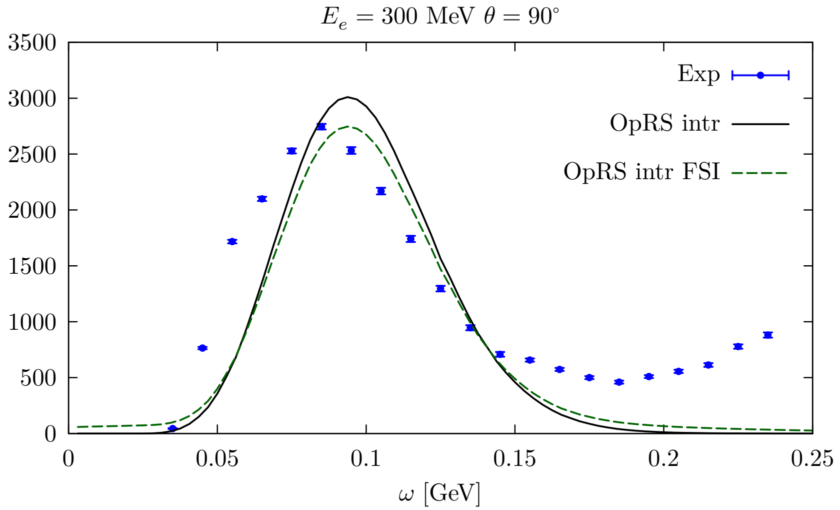
^{4}He-e$^-$ cross sections from the SCGF Spect. Fnct.

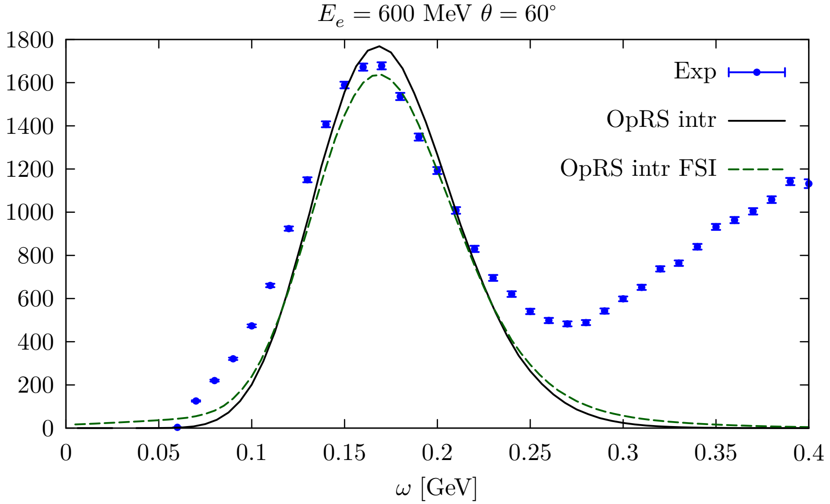
PW Impulse approximation:





Adding FSI:





Based on the saturating chiral N2LO-sat nuclear force

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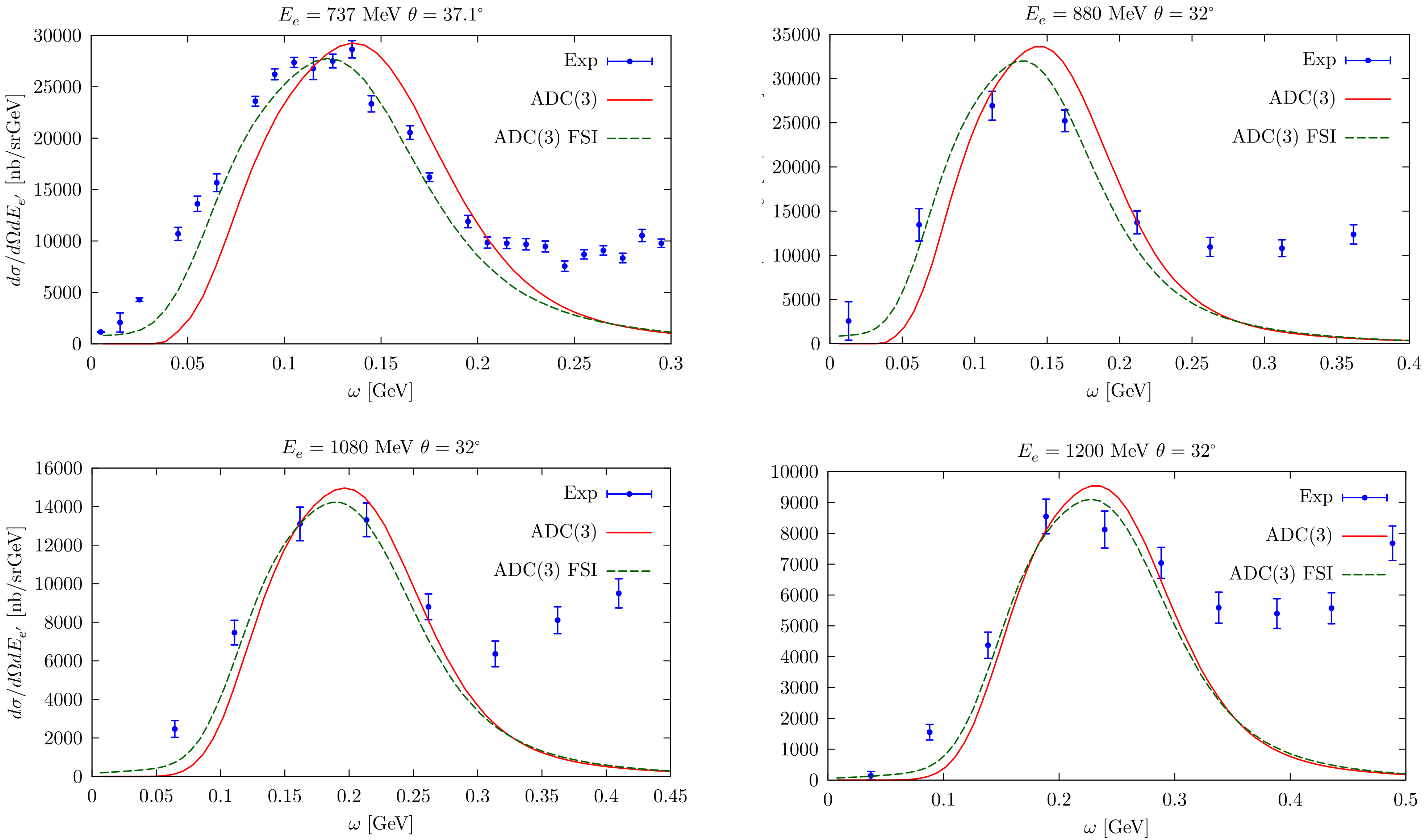
N. Rocco, CB, arXiv:1803.00825 (Phys. Rev. C in print)

^{16}O-e⁻ cross sections from the SCGF Spect. Fnct.

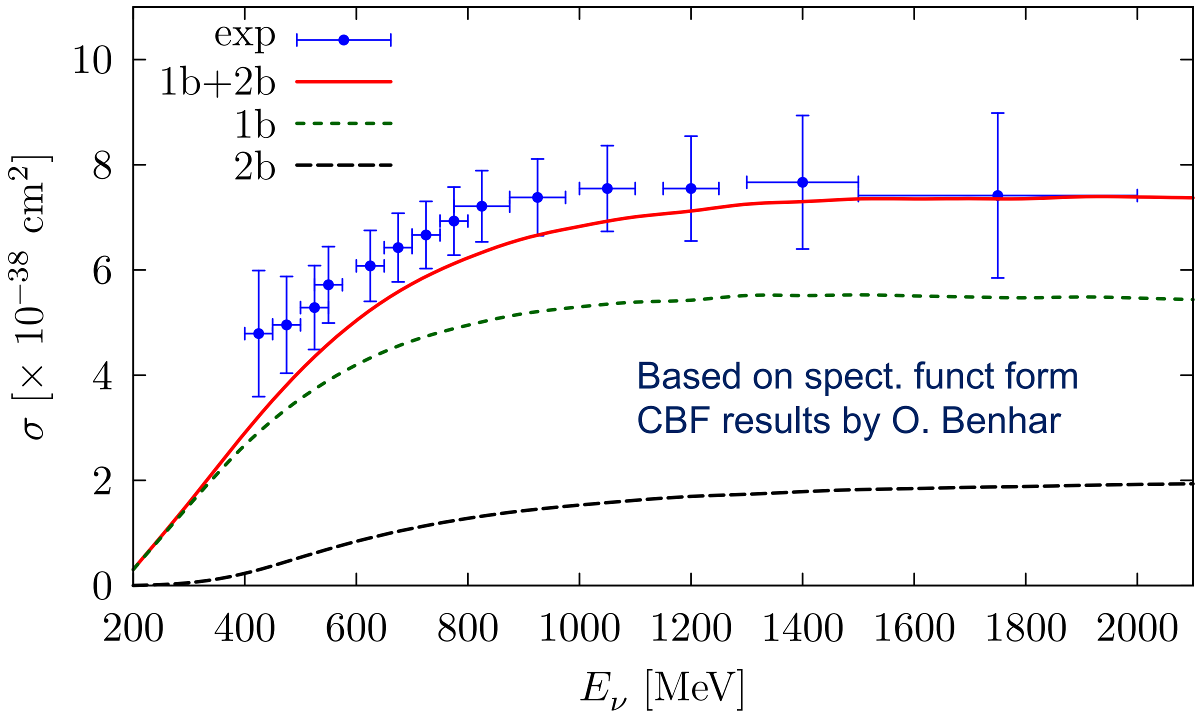


Based on the saturating chiral N2LO-sat nuclear force

N. Rocco, CB, arXiv:1803.00825 (Phys. Rev. C in print)

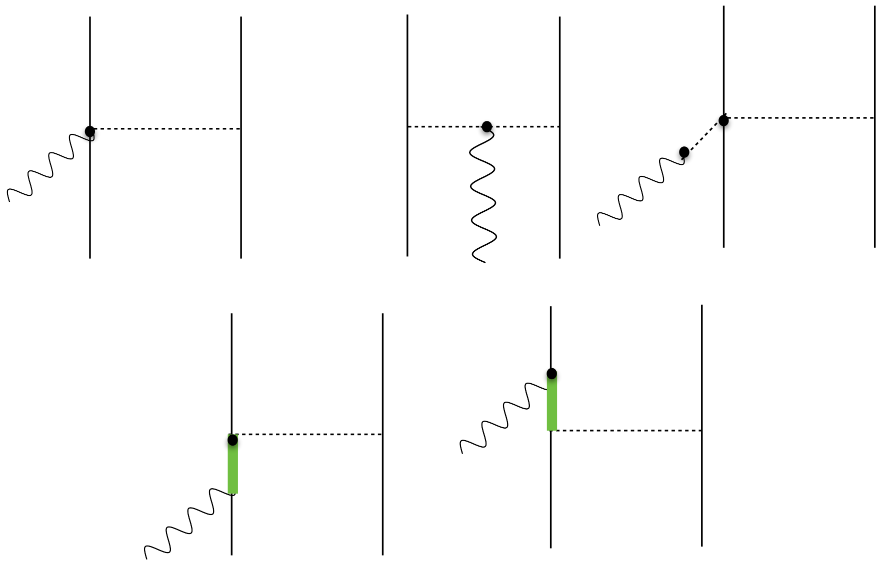
Role of two-body (meson exchange) currents in ν-A

CC0π total cross section: MiniBooNE data



The 2p2h contribution is needed to explain the magnitude of the total cross section

- Two-body diagrams contributing to the axial and vector responses



- Preliminary implementation discards 1b-2b interference:

$$W^{\mu\nu}_{2p2h} = W^{\mu\nu}_{ISC} + W^{\mu\nu}_{MEC} + \cancel{W^{\mu\nu}_{int}}$$

Calculations by N. Rocco, see also talk by O. Benhar afterward

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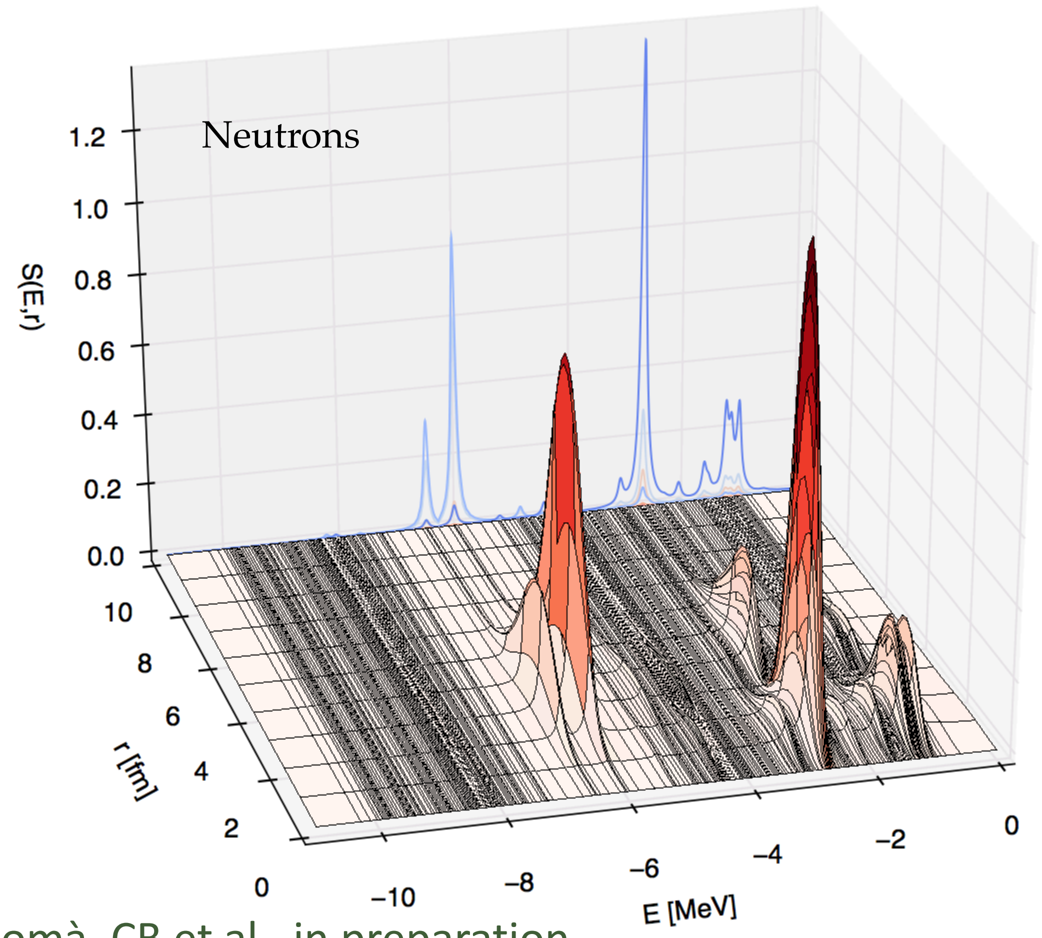
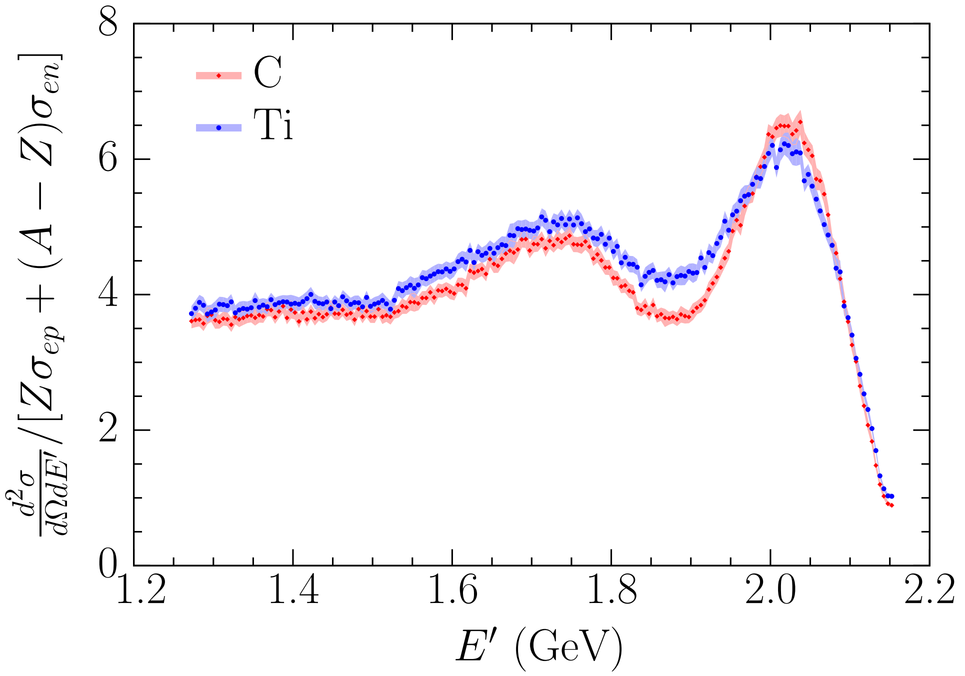
Spectral function for ^{40}Ar



V. Somà, CB et al., in preparation



- Experimental datat now available for Jlab: H. Dai et al., arXiv:1803.01910
- Ab initio simulations based on the ADC(2) truncation of the N2LO-sat Hamiltoninan

➔ Validation of initial state correlation before they are implementer in neutrino-^{40}Ar simulations

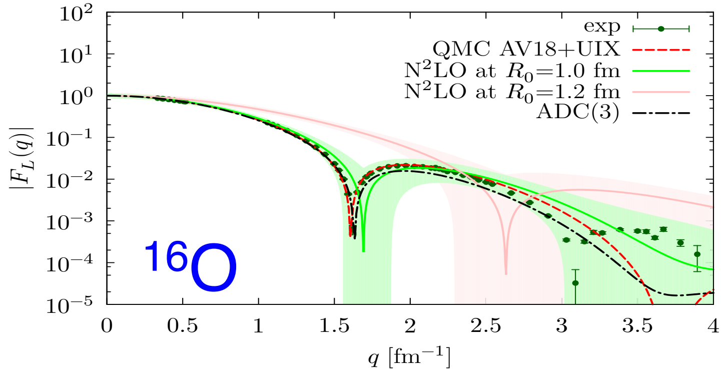
Summary

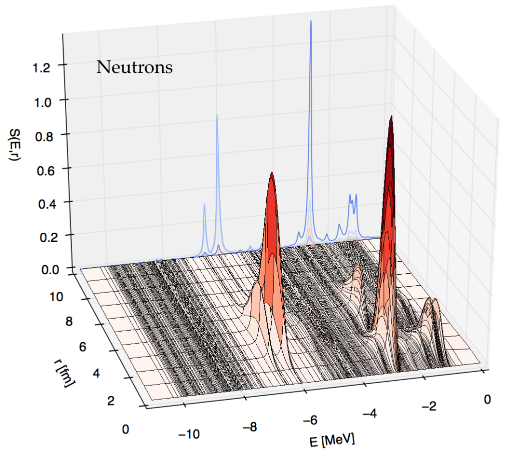
Thank you for your attention!!!

Saturating chiral interactions and 3N forces:

→ *Description of nuclear g.s. in the pf shell is improved-especially in the trends w.r.t. iso-sopin asymmetry.*

→ *Radii: newer generations of chiral interaction can give satisfactory radii.*





Applications to electron and neutrino scattering:

→ *Spectral functions (not only for 1-body!) are extracted naturally from the SCGF formalism.*

→ *good reproduction of charge/momentum distribution and electron scattering.*

→ *Inclusion of electroweak currents (1b and 2b) underway (by N. Rocco).*

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A. Cipollone, N. Rocco
A. Idini, **F. Raimondi**

cea
energie atomique • energies alternatives

V. Somà, T. Duguet

ECT*

A. Carbone

TRIUMF

P. Navratil

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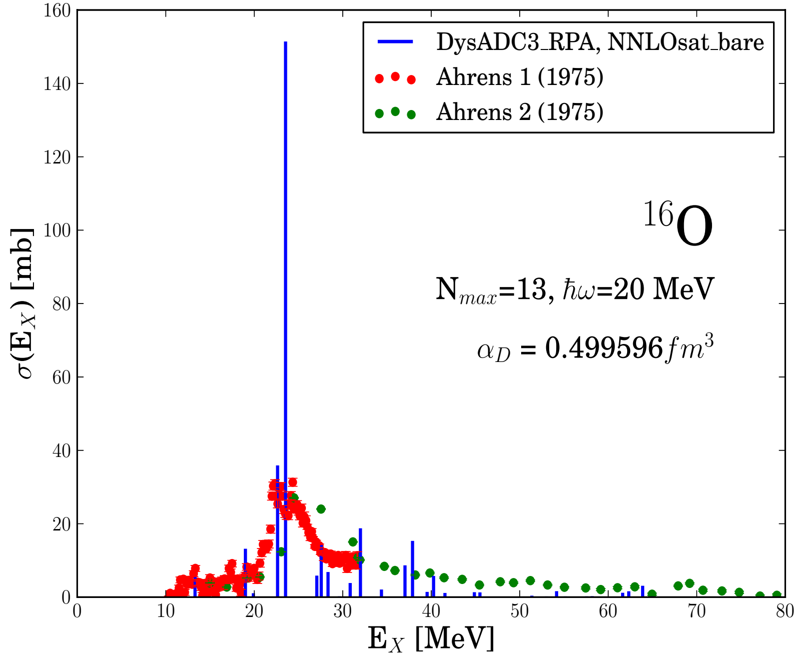
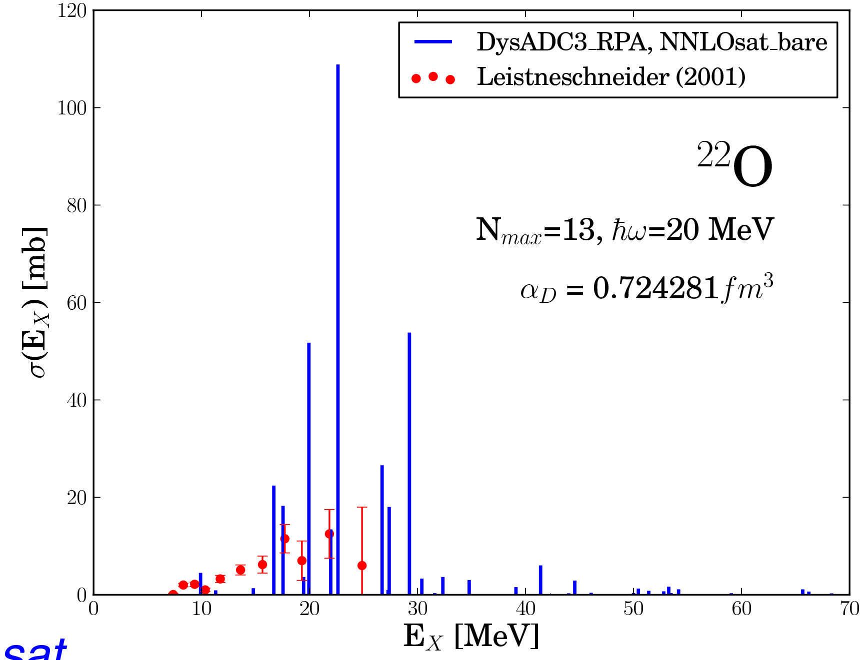
Results for Oxygen isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation





NNLO*sat*

- GDR position of ^{16}O reproduced
- Hint of a soft dipole mode on the neutron-rich isotope

Dipole polarizability α_D (fm^3)

Nucleus	SCGF	CC/LIT	Exp
^{16}O	0.50	0.57(1)	0.585(9)
^{22}O	0.72	0.86(4)	0.43(4)

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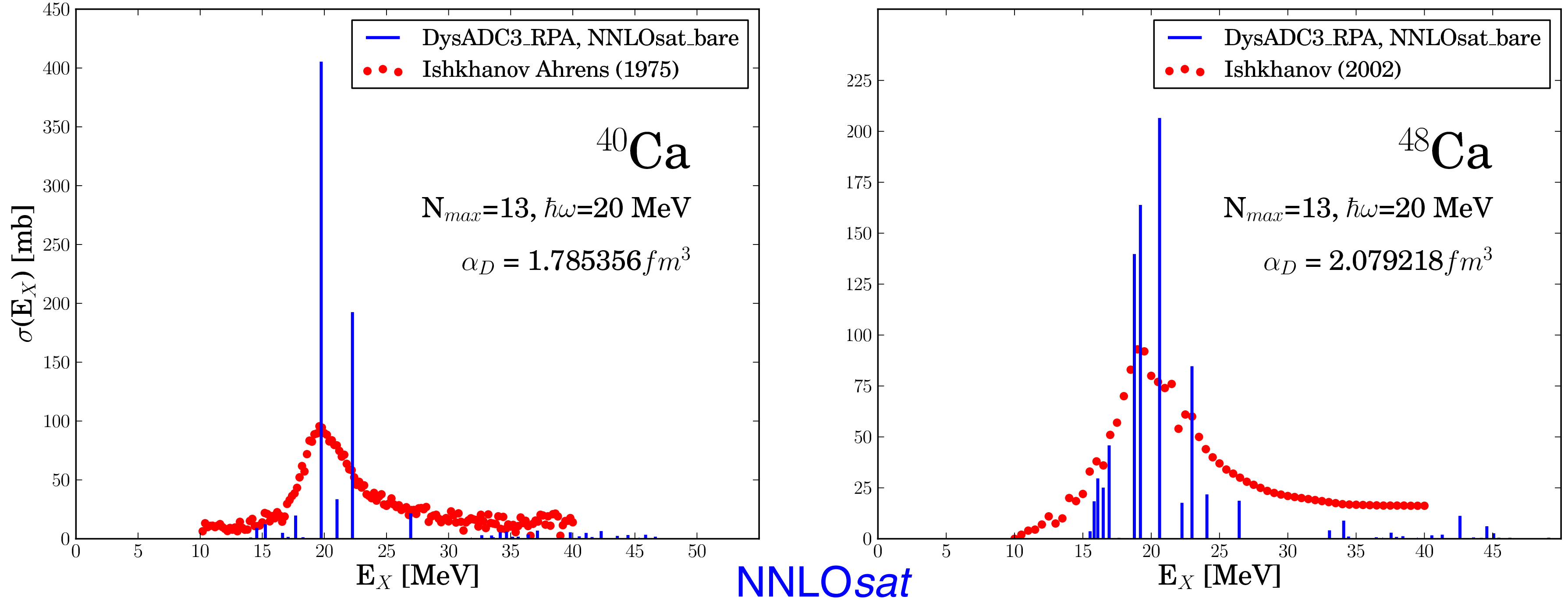
F. Raimondi, CB, arXiv:1711.04698 + in prep.

Results for Calcium isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation



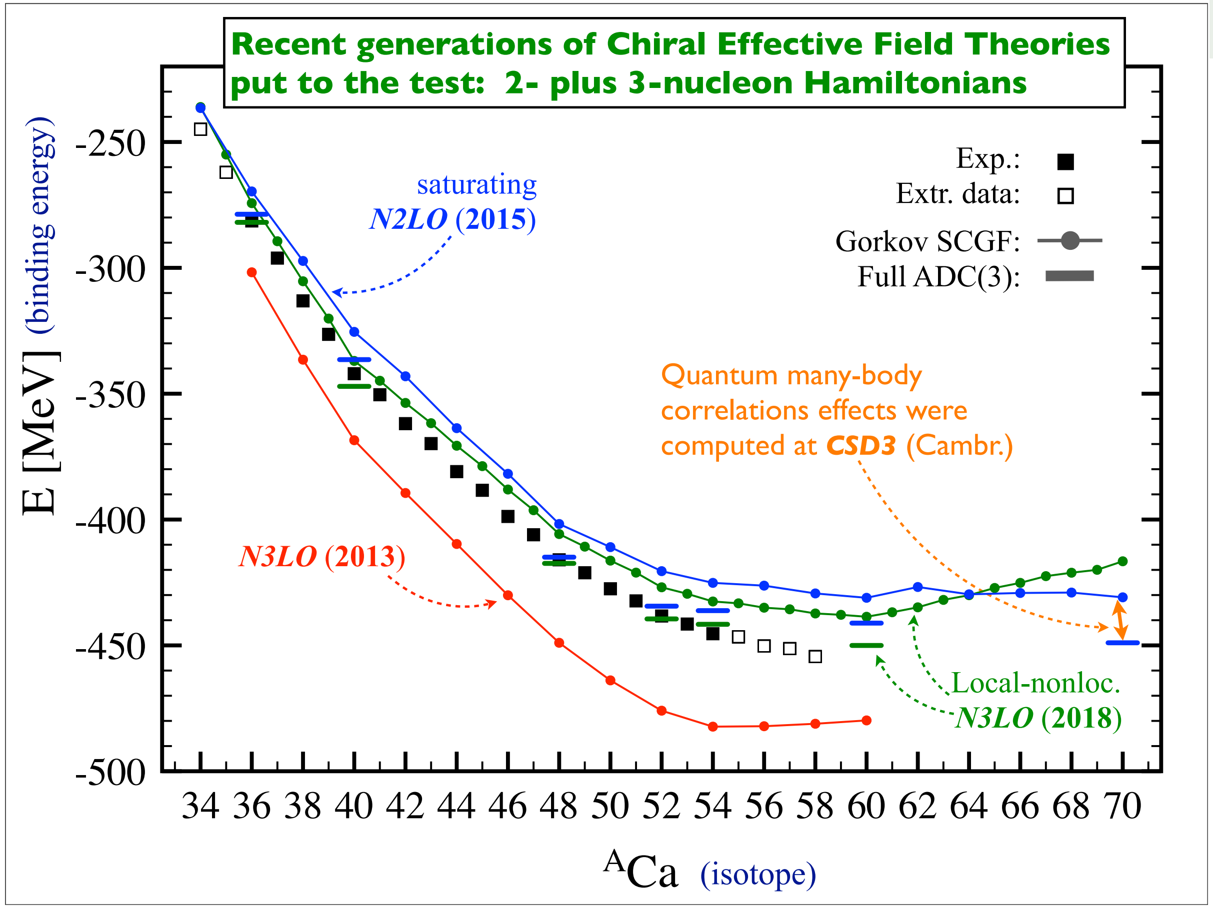
NNLO*sat*

- Positions of GDRs reproduced

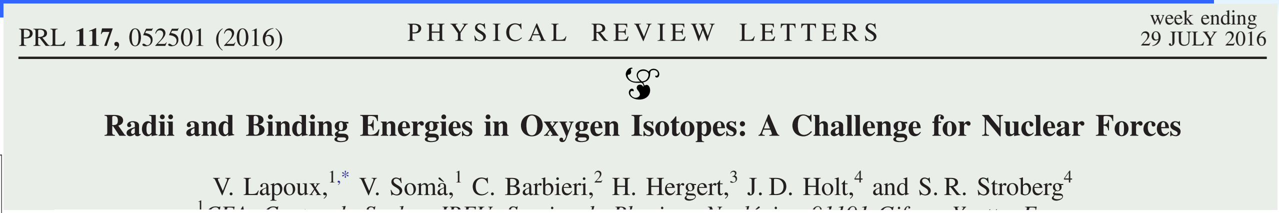
Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{40}Ca	1.79	1.47 $(1.87)_{thresh}$	1.87(3)
^{48}Ca	2.08	2.45	2.07(22)

F. Raimondi, CB, arXiv:1711.04698 + in prep.

Comparison of nuclear forces – ^{A}Ca and ^{A}O

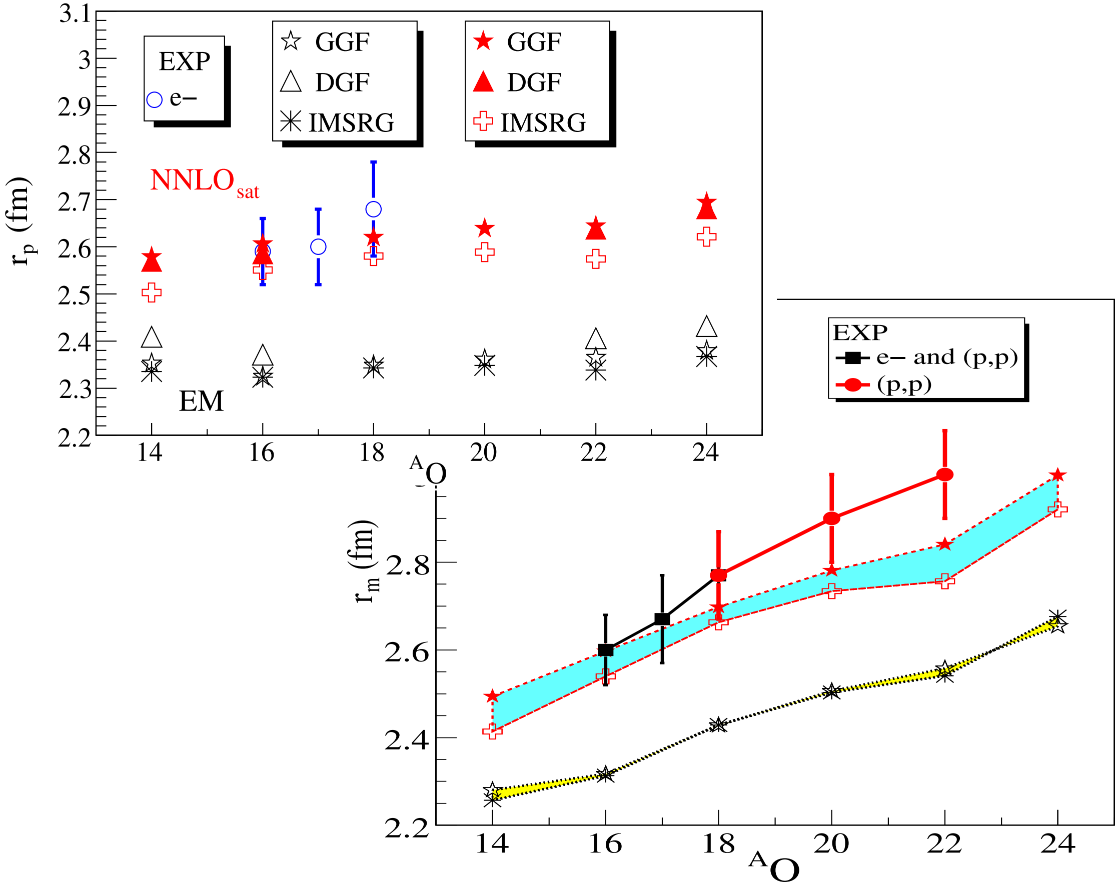


V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation


PRL 117, 052501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

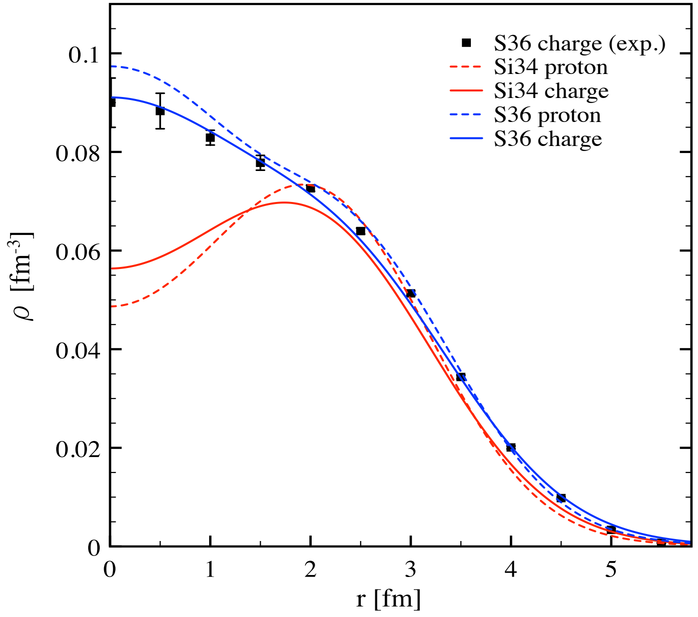
Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

V. Lapoux,[1,*] V. Somà,[1] C. Barbieri,[2] H. Hergert,[3] J. D. Holt,[4] and S. R. Stroberg[4]



Saturation and radii now predicted *accurately*!

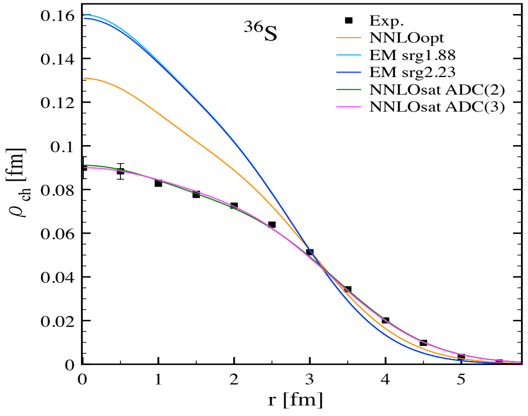
Bubble nuclei… ^{34}Si prediction

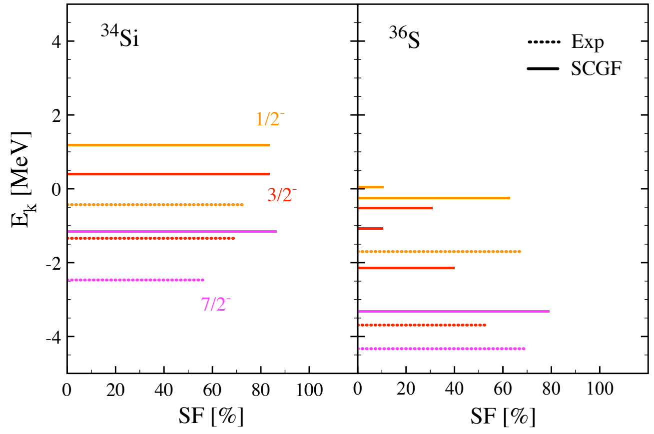


Duguet, Somà, Lecuse, CB, Navrátil,
Phys.Rev. C**95**, 034319 (2017)

- ^{34}Si is unstable, charge distribution is still unknown
- Suggested central depletion from mean-field simulations
- *Ab-initio* theory confirms predictions
- Other theoretical and experimental evidence:
  Phys. Rev. ***C 79****, 034318 (2009),*
  Nature Physics ***13****, 152–156 (2017).*

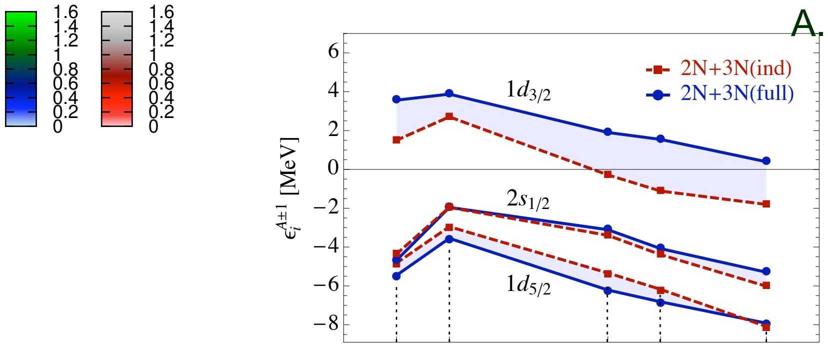
Validated by charge distributions and neutron quasiparticle spectra:

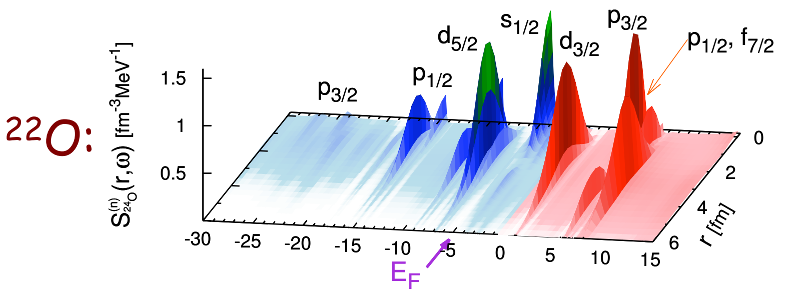


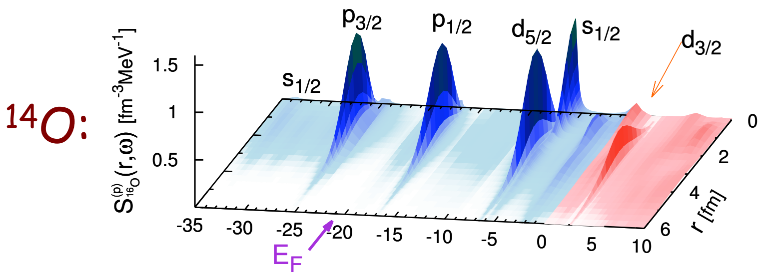


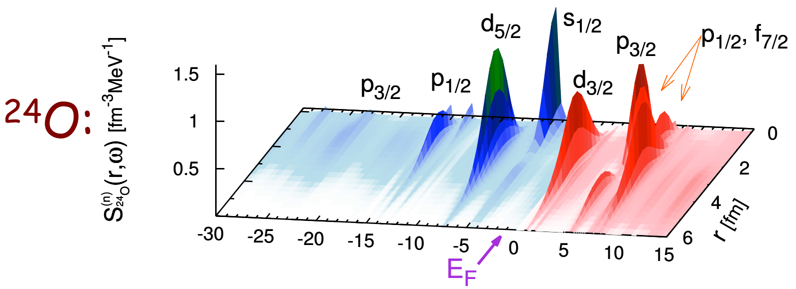
Neutron spectral function of Oxygens

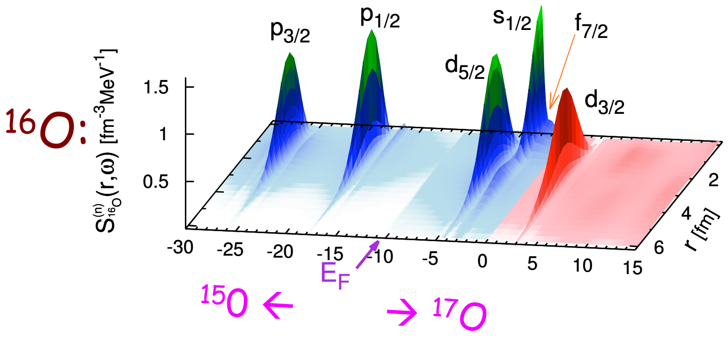
A. Cipollone, CB, P. Navrátil, *Phys. Rev. C* **92**, *014306 (2015)*

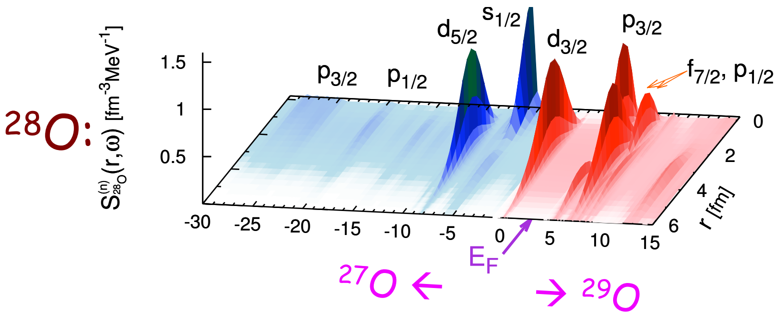












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